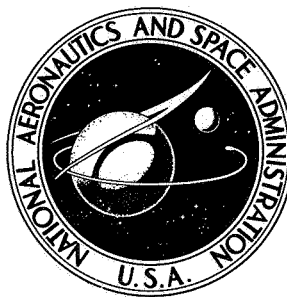


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**FLIGHT-DETERMINED AERODYNAMIC
PROPERTIES OF A JET-AUGMENTED,
AUXILIARY-FLAP, DIRECT-LIFT-CONTROL
SYSTEM INCLUDING CORRELATION
WITH WIND-TUNNEL RESULTS**

by L. Stewart Rolls, Anthony M. Cook, and Robert C. Innis

*Ames Research Center
Moffett Field, Calif.*

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SUMMARY

Flight tests were conducted on the modified Boeing 367-80 prototype, jet-transport aircraft to determine the aerodynamic characteristics of an externally blown auxiliary-flap system. These flight data are compared with data from a similarly modified one-third scale model in the Ames 40- by 80-Foot Wind Tunnel. Flight data for dynamic steps of the auxiliary flaps indicate a lower peak normal acceleration capability than that indicated by the flight data for static steps; the lower peak is attributed to a rate limit of the flap actuator. The pilots reported an improvement in the landing flare and touchdown tasks resulting from the increased vertical response of the direct-lift-control system.

INTRODUCTION

The continuing trend toward larger and larger transport aircraft, with the corresponding increases in weight and density, has resulted in reduced response especially in the longitudinal direction. This reduction could result in insufficient precision of control for normal service operation, particularly in the more demanding situations of minimum visibility landings. Because of the possibility of marginal flight-path control in the landing approach of these aircraft, methods for improving flight-path control are being investigated. One method that has shown promise is direct-lift control (DLC). Several devices have been considered for the control of lift for a DLC system. For the transport airplane described in reference 1 wing spoilers were used, whereas, for the fighter of reference 2, a wing flap was used. Another method of controlling the lift is with a thrust-augmented flap system. Wind-tunnel tests have shown that a plain flap mounted in a position to be blown externally by the jet engine exhaust will furnish high lift, and a small auxiliary flap added to the main flap and rapidly actuated will supply a direct-lift method of flight-path control (ref. 3).

To obtain operational experience with a large sized aircraft using the thrust-augmented, auxiliary-flap type of DLC, an extensive research program

was initiated with a large-scale model in the Ames 40- by 80-Foot Wind Tunnel, and the Boeing 367-80 aircraft, the prototype of the Boeing 707-jet transport aircraft. The thrust-augmented flap system was initially tested on a one-third scale model in the wind tunnel. The Boeing Company then modified (under NASA contract) the flap system on the airplane. An extensive flight program was then conducted to evaluate the wind-tunnel aerodynamic predictions and evaluate the DLC capabilities of the auxiliary flap in various linear and non-linear type landing approaches.

This report presents the flight-measured aerodynamic characteristics, a comparison of the flight and wind-tunnel measurements for several basic flap deflections, and a pilot's comments on the characteristics of the airplane as affected by the auxiliary flap.

SYMBOLS

A_z	normal acceleration at center of gravity, g
b	wing span, ft
BLC	boundary-layer control
c	chord, ft
\bar{c}	mean aerodynamic chord, $\frac{2}{S} \int_0^{b/2} c^2 dy$, ft
C_D	drag coefficient, $\frac{\text{drag}}{qS}$ (thrust component of inboard engines included)
C_L	lift coefficient, $\frac{\text{lift}}{qS}$
C_T	thrust coefficient, $\frac{\text{gross thrust}}{qS}$ (inboard engines only)
C_μ	BLC momentum coefficient, $\frac{\text{momentum} \times \text{jet velocity}}{qS}$
$\frac{dh}{dt}$	rate of change of altitude, ft/sec
$\frac{dv}{dt}$	rate of change of airspeed, ft/sec
F.S.	flap station, in.
g	acceleration due to gravity, 32.2 ft/sec ²
h	altitude, ft
LE	leading edge

N_2	high pressure compressor rotational speed, percent of maximum (100 percent $N_2 = 9655$ rpm)
q	dynamic pressure, lb/ft ²
S	reference wing area, ft ²
t	time, sec
T_{out}	sum of net thrust of outboard engines, lb
TE	trailing edge
V	velocity, ft/sec
W	airplane gross weight, lb
W.S.	wing station, in.
y	spanwise distance perpendicular to the plane of symmetry, ft
α	wing angle of attack, deg
δ_f	angle of deflection of wing TE main flap, downward from wing chord plane, deg
$\delta_{f_{aux}}$	angle of deflection of wing TE auxiliary flap, relative to main flap chord plane (positive TE down), deg

DESCRIPTION OF EQUIPMENT AND TESTS

Airplane

The flight investigation was conducted on the Boeing 367-80 airplane, which is the prototype of the C/KC-135 jet-transport/tanker airplane and the 707 series commercial transport. Figure 1 is a photograph of the airplane and figure 2, a two-view drawing with a list of basic dimensions. For this investigation, the 367-80 was equipped with fixed leading-edge slats on the outboard sections and a fixed Kruger flap over the outer half of the section between the fuselage and the inboard engine as shown in figure 1(a).

The basic wing and flap system of the 367-80 airplane has been extensively modified for investigating slow speed flight. The modifications and their aerodynamic characteristics are described in references 4 and 5, but basically they include replacing the slotted flaps of the original airplane with a plain flap and installing a high-pressure blowing-type, boundary-layer-control system. The modification also included a thrust modulation system to permit operation at high engine speeds to increase effectiveness of the boundary-layer-control system; thrust modulation, however, was not used in this investigation.

To furnish the direct-lift-control (DLC) capability investigated in this program the aft 0.40c of the flap on the 367-80 airplane was replaced with a slotted auxiliary flap operated by hydraulic actuators to produce the required high deflection rates for the DLC function (ref. 6). The flap installed on the aircraft duplicated, as closely as manufacturing capabilities would permit, the flap system tested in the Ames 40- by 80-Foot Wind Tunnel. A typical section of the flap as installed on the aircraft is shown in figure 3. During these tests, the gross weight of the aircraft varied from 170,000 to 145,000 pounds and the center of gravity was at approximately 30 percent of the wing mean aerodynamic chord.

Flight Tests and Data Reduction

The Boeing 367-80 airplane carries an extensive data recording system. The bulk of the quantities are recorded on magnetic tapes which are then processed on automatic digital computing machines. All the flight data were reduced by the Boeing Company as a part of this program contract.

The lift and drag coefficients were determined during the steady portion of a maneuver in which the pilot would select the prescribed flap and power condition and would gradually increase angle of attack. During each run the pilot would periodically establish a stabilized airspeed and angle-of-attack condition which was used for data reduction purposes. The lift coefficients are based on the relation:

$$C_L = \frac{W_{Az}}{qS} - \frac{T_{out} \sin \alpha}{qS}$$

which corrects the data to 1-g flight and accounts for the vertical component of the thrust. The drag coefficient data are based on the drag determined from the relation:

$$D = T_{out} \cos \alpha - \frac{W}{g} \left(\frac{dv}{dt} \right) - \frac{W}{V} \left(\frac{dh}{dt} \right)$$

The angle-of-attack data were obtained from measurements of the position of a vane mounted on a boom 17 feet ahead of the nose of the airplane. This vane was calibrated by measurements of pitch attitude and flight path made during steady, unaccelerated flight.

It is customary in the evaluation of a jet-augmented flap system to include the thrust components in the aerodynamic coefficients because the coefficients are dependent on the thrust coefficient values. Therefore, the aerodynamic data presented in this report include the thrust components about the appropriate axis for the two inboard engines. The thrust of only the inboard engines was included in the data since the jet exhausts of only these engines impinge on the flap.

Wind-Tunnel Model and Data Reduction

The wind-tunnel model was constructed to be representative of a four-engine turboprop, swept-wing, subsonic transport, and had a wing with a quarter chord sweep of 35° , aspect ratio of 6.46, dihedral of 6° , and incidence of 2° . Figure 4 is a photograph of the model mounted in the Ames 40- by 80-Foot Wind Tunnel. The wing was equipped with a full-span leading-edge slat which was deflected 35° with respect to the wing chord plane and was linearly tapered from 0.20c at the root to 0.18c at the tip. The fuselage was circular in cross section, the largest section being 4 feet in diameter; the model had conventional swept vertical and horizontal tails. Details of the flap system, which is composed of two parts, the main flap and the auxiliary flap, are shown in figure 5. The auxiliary flap has a chord of 0.42c of the total flap chord. The model was equipped with a shroud-mounted, fixed blowing nozzle which spanned the full extent of the flap. Air for this BLC system was obtained by bleeding air from the compressors of the four jet engines mounted on the model. The T-58-6A jet engines, located at 0.41 and 0.71 of the wing semispan, were modified to operate as conventional jet engines. To simulate closely the exhaust wake of a fan-jet engine, ejectors were mounted behind the inboard engines on the wind-tunnel model. A jet exhaust deflector was also mounted behind the inboard engine ejector to aid the jet impingement on the model flap to duplicate closely that expected on the airplane since there was some difference in engine locations. Standard wind-tunnel wall corrections were applied to all data where applicable. More details of the model and the test results are contained in reference 7.

RESULTS AND DISCUSSION

Flight Aerodynamic Characteristics

Figures 6, 7, and 8 present the flight-measured aerodynamic lift and drag characteristics. These data are presented for three auxiliary-flap positions and various constant engine power conditions for each of three basic flap deflections. As each lift and drag curve was obtained at a constant engine power condition, the thrust coefficient varied as the airspeed was reduced during a stall; hence, the variation of thrust coefficient is also presented in each figure. Since the total exit momentum of the jets affects the augmentation of the flap lift, the thrust coefficients are based on the engine gross thrust. In this airplane, however, the flaps extended only through the jet exhaust of the inboard engines; consequently, these thrust coefficients are the sum of gross thrusts of these engines. These data show a consistent variation of angle of attack and drag coefficient with lift coefficient and thrust coefficient for each auxiliary-flap setting. In some cases, only a limited number of data points were obtained, due to the difficulty of selecting equal increments during the flights. This caused some difficulty in fairing the curves; and the maximum lift coefficients were not obtained because of the pilots' terminating the run at the onset of buffet instead of the stall.

Figures 9 and 10 summarize the auxiliary flap effectiveness and jet augmentation effect, respectively. These data are presented for constant angles of attack as C_{Lmax} was not obtained in all cases. Figure 9 presents the auxiliary flap effectiveness for each of the three main flap settings at power for level flight. These data show the auxiliary flaps to decrease in effectiveness at deflections above 20° . Figure 10 presents the jet augmentation effects for the main flap set at 40° and an angle of attack of 12° , the highest angle of attack for which data were available for all configurations.

To obtain the highest lift coefficients possible, and, consequently, lower approach speeds, the BLC system installed on the Boeing 367-80 was utilized during this program. The thrust-modulating system developed to permit flight at higher duct pressure in the BLC system (refs. 4 and 5) was not used during these tests, so the duct pressures and momentum coefficients were a function of conventional jet engine speed. Bleed air from the compressors of all four jet engines was used to supply air to the BLC system. The variation of lift coefficient with momentum coefficient for a constant thrust coefficient and selected flap configuration is presented in figure 11. This curve shows the typical increase in lift coefficient as momentum coefficient increases until the air flow becomes attached and then levels off. All data presented in this report are for a BLC-on configuration and, while there is some variation of C_μ with C_T , the C_μ is high enough to assure attachment for all cases except for 50° main flap at 60 percent N_2 .

The observed flight characteristics of the aircraft during these tests indicated the flaps had little effect on the stalling characteristics and no rolloff or pitchup was noted. Visual observation of the tufts mounted on the flap indicated the air flow was still good at high angles of attack. The onset of buffet occurred at approximately 12° angle of attack for all flap conditions and appeared to be caused by leading-edge separation on the wing, perhaps inboard of the Kruger flap.

Direct-Lift Control

The auxiliary flap was installed on the airplane to determine its ability to quickly change the airplane lift characteristics for DLC on landing approaches. The auxiliary flap was initially set at a position of 10° trailing edge down, with respect to the main flap, and modulated about this setting to provide up or down changes in the flight path. The increment of normal acceleration, g , possible with the auxiliary flap system is presented in figure 12. These data were computed for an angle of attack of 4° , which corresponds to about 1.2 times the stall speed based on an airplane gross weight of 150,000 pounds with 40° main flap deflection. To verify the g produced by the auxiliary flaps a series of runs were made in flight with the auxiliary flap dynamically stepped in $\pm 10^\circ$ and $\pm 20^\circ$ increments at nearly constant attitude. Time histories of several airplane parameters during one of these abrupt auxiliary flap steps are shown in figure 13. This maneuver was performed by commanding an abrupt voltage change to the electrohydraulic valve of the flap actuator, and the flap positions show the motion of each auxiliary flap section. The aircraft's autopilot system counteracted the aircraft's nose-down pitching moment caused by the auxiliary flap motion to maintain a nearly

constant aircraft attitude. The corresponding changes in elevator angle are shown in this figure. Unfortunately, the elevator angle for flap moment compensation was programmed by the flap command voltage and not by flap position, which resulted in an initial nose-up pitch of the airplane. Also shown in this figure is the change in normal acceleration, measured at the aircraft's center of gravity, resulting from the auxiliary flap step. A comparison of the maximum normal acceleration generated during a dynamic step with the capability shown in figure 12 indicates that the dynamic capability is less than that indicated from static data and the increased acceleration lasted for a longer period of time than expected. The airplane responses were calculated to explain those differences between the static and dynamic cases and are presented in figure 14. In this figure, the calculated responses are presented for three conditions that represent: (a) the normal acceleration response assuming an instantaneous step of the auxiliary flap, (b) assuming the measured flap rate as shown in figure 13, and (c) the curve of (b) corrected for the amount of elevator deflection and pitching velocity measured in flight as shown in figure 13. The curve computed after accounting for these effects is then compared with the flight-measured normal acceleration curve. The general agreement between this computed response curve and the measured response curve indicates the bulk of the differences between the dynamic and static auxiliary flap effectiveness can be attributed to a low rate of movement of the auxiliary flap and the corresponding aerodynamic changes on the aircraft during this time interval. Wing bending, vibration, accelerometer characteristics, and other second-order effects probably constitute the bulk of the differences unaccounted for.

To show the advantage of a DLC system, figure 15 compares the airplane response to an elevator step and to a DLC auxiliary flap step. The rise in normal acceleration at the center of gravity is immediate with the DLC system, whereas a slight reduction occurs with the elevator step. The airplane arrived at a given normal acceleration level approximately 0.5 second earlier from an auxiliary flap step than occurred with an elevator step. If the auxiliary flap actuation were more rapid, this time improvement for the DLC system would be even more dramatic.

Flight and Wind-Tunnel Data Correlation

Figure 16 compares the flight and wind-tunnel data for main flap deflections of 30° , 40° , and 50° with the auxiliary flap deflected 10° . Since the wind-tunnel data were measured at a constant thrust coefficient, and the flight data at constant engine power, the lift and drag data from the tunnel were corrected to the same thrust coefficient and momentum coefficient occurring in the flight data. In most cases, at the lower angles of attack, the wind-tunnel data and flight data agree; however, as angle of attack is increased, the difference between flight and wind-tunnel data becomes larger. Figure 17 compares the auxiliary-flap effectiveness as computed from flight with that from the wind-tunnel data. These results indicate that the flap effectiveness measured in the wind tunnel is slightly greater than that measured in flight. Comparison of the airplane and wind-tunnel data shown in figure 16 indicates primarily wing or leading-edge differences between the

model and the airplane, whereas the discrepancies in model and airplane normal acceleration capabilities shown in figure 17 are primarily the result of differences in flap geometry, shape of flap slot, or impingement.

Pilot Opinion

A DLC system could significantly affect the pilot's ability to control an aircraft's flight path during instrument approaches and while making the flare and touchdown during landings. The use of the Boeing 367-80 aircraft in a program to evaluate a number of landing approach schemes (ref. 8) gave the pilots an opportunity to observe the characteristics of a DLC system during this demanding flight regime. Standard ILS, steep, two-segment, curved, and decelerating approaches were flown both with and without the DLC system operating. During these approaches, the DLC operation was coupled with the longitudinal control system which limited the amount of DLC available for flight-path control to some function of longitudinal control motion. Direct operation of the DLC, which would permit more effective use of the A_z capability of the auxiliary flap, was not used in this investigation because of the increased complexity of the pilot's task with a separate controller, which previous unpublished tests had shown to be undesirable. The characteristics of the DLC system as evaluated in these approaches are shown in figure 18.

Approaches were flown at speeds varying from 106 to 120 knots with 40° flap deflection, and 135 to 145 knots at 50° . During these approaches, the pilot indicated that the DLC improved very little, if any, his ability to track the ILS glide slope with the guidance system used; this is not surprising since the airplane exhibited good longitudinal dynamic characteristics with or without DLC. Most of the pilots felt that the quickened vertical response afforded by the DLC during the flare and touchdown provided more precise control of the touchdown point and rate of sink. The pilots also felt the DLC provided an increased feeling of security, particularly close to the ground, because they could more rapidly arrest a high rate of descent. The lowest speed evaluated with the 40° main flap setting was 106 knots, which was equivalent to 1.2 times the stall speed with approach power ($1.2V_S$). At this speed the flight-path control with DLC was still good. A few approaches were also made at about the same speed with the main flap at 50° deflection. In this case the positive g response of the DLC was too low because of the low flap actuation rates and low auxiliary-flap effectiveness.

CONCLUDING REMARKS

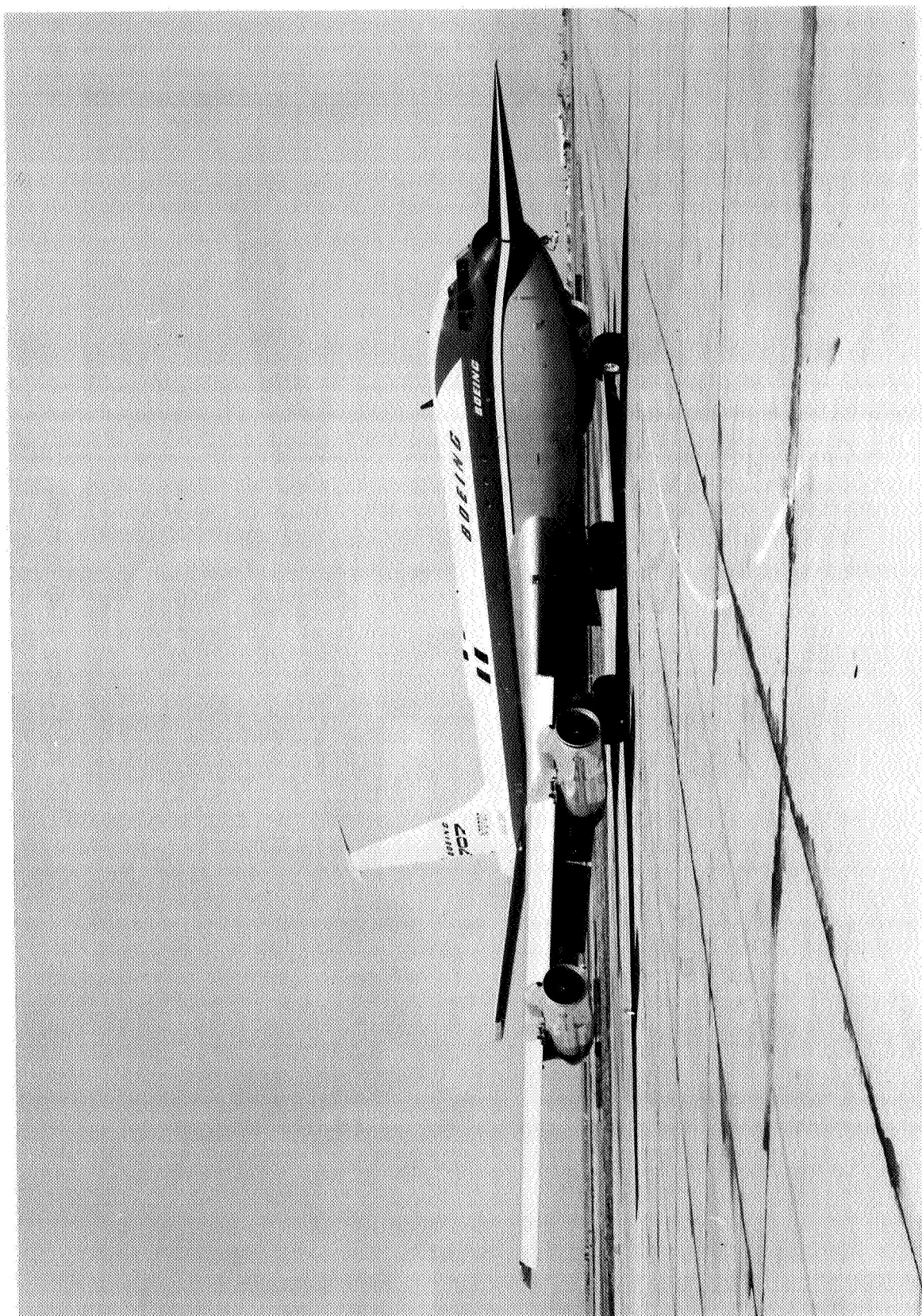
The lift and drag characteristics of an externally blown, auxiliary-flap system were measured in flight with a large transport-type jet aircraft. An auxiliary-flap step would produce equal normal accelerations approximately 0.5 second sooner than an elevator alone step. Good correlation was obtained with these flight characteristics and those obtained on an approximately one-third scale model in the Ames 40- by 80-Foot Wind Tunnel. The dynamic maximum normal acceleration capabilities of the flap system were somewhat reduced from the static lift capability due to a rate limit of the flap actuation system.

Approaches were flown at 106 knots ($1.2V_S$) at 40° flap deflection and the pilot felt that flight-path control with DLC was still good. The pilots also appreciated the quickened vertical response available from DLC during the flare and touchdown tasks.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., 94035, Feb. 18, 1969
733-02-00-01-00-21

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A-39225-35

(a) General view.

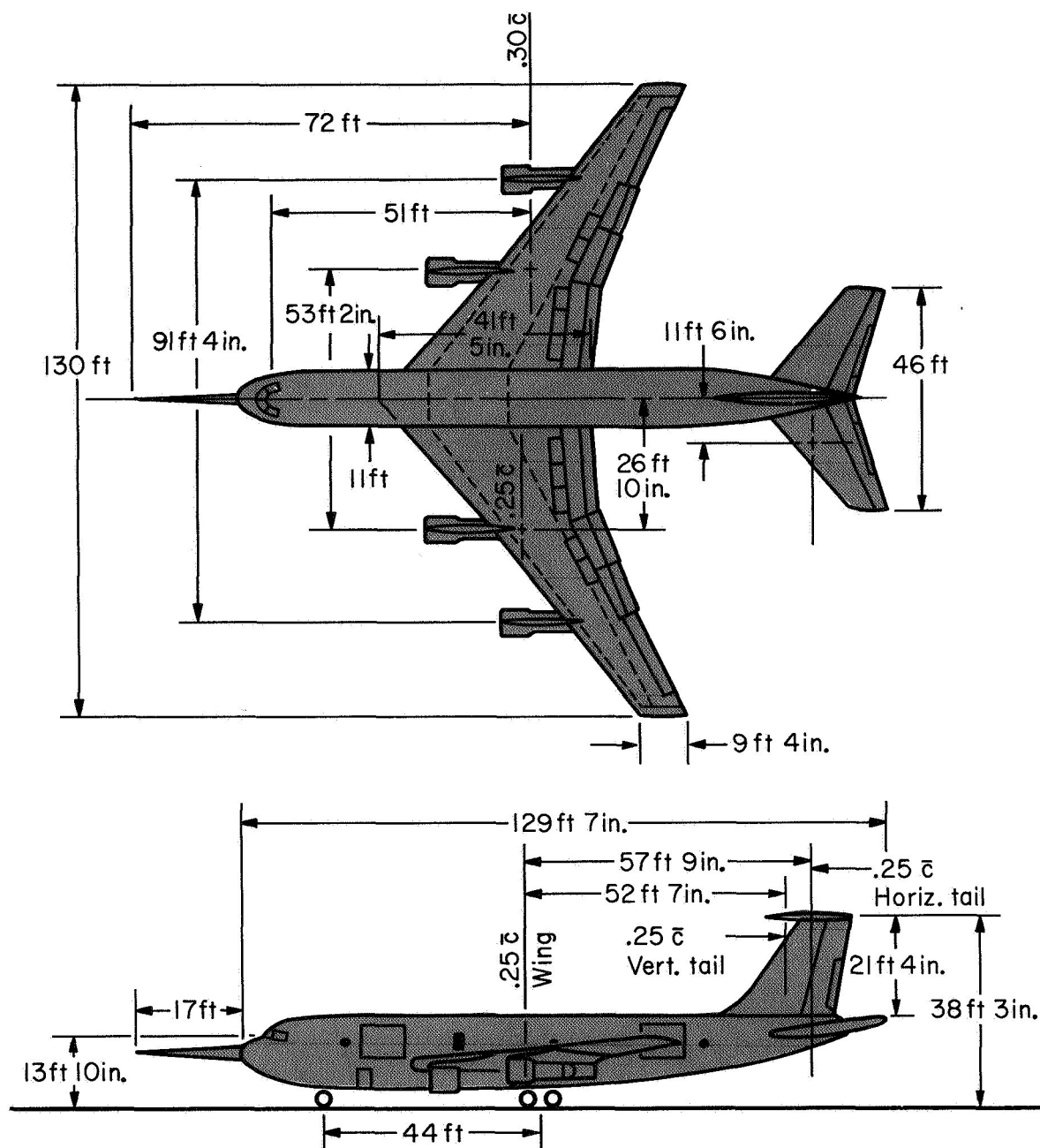
Figure 1.- Airplane.



(b) Auxiliary flap system.

Figure 1.- Concluded.

A-39225-39



WING		HORIZONTAL TAIL		VERTICAL TAIL	
Area	2821.36 ft ²	Area	625 ft ²	Area	312 ft ²
Aspect ratio	6.0 ⁰	Aspect ratio	3.37	Aspect ratio	1.46
Sweep (0.25c)	35 ⁰	Sweep (0.25c)	35 ⁰	Sweep	31.0 ⁰
Incidence	2.0 ⁰	Taper ratio	0.421	Taper ratio	0.45
Dihedral	7.0 ⁰	Dihedral	7.0 ⁰	Tail volume	0.0447
c	20.05 ft	Tail volume	0.638		

C. G. TRAVEL RANGE: 28-32 PERCENT c

Figure 2.- Geometric details of airplane.

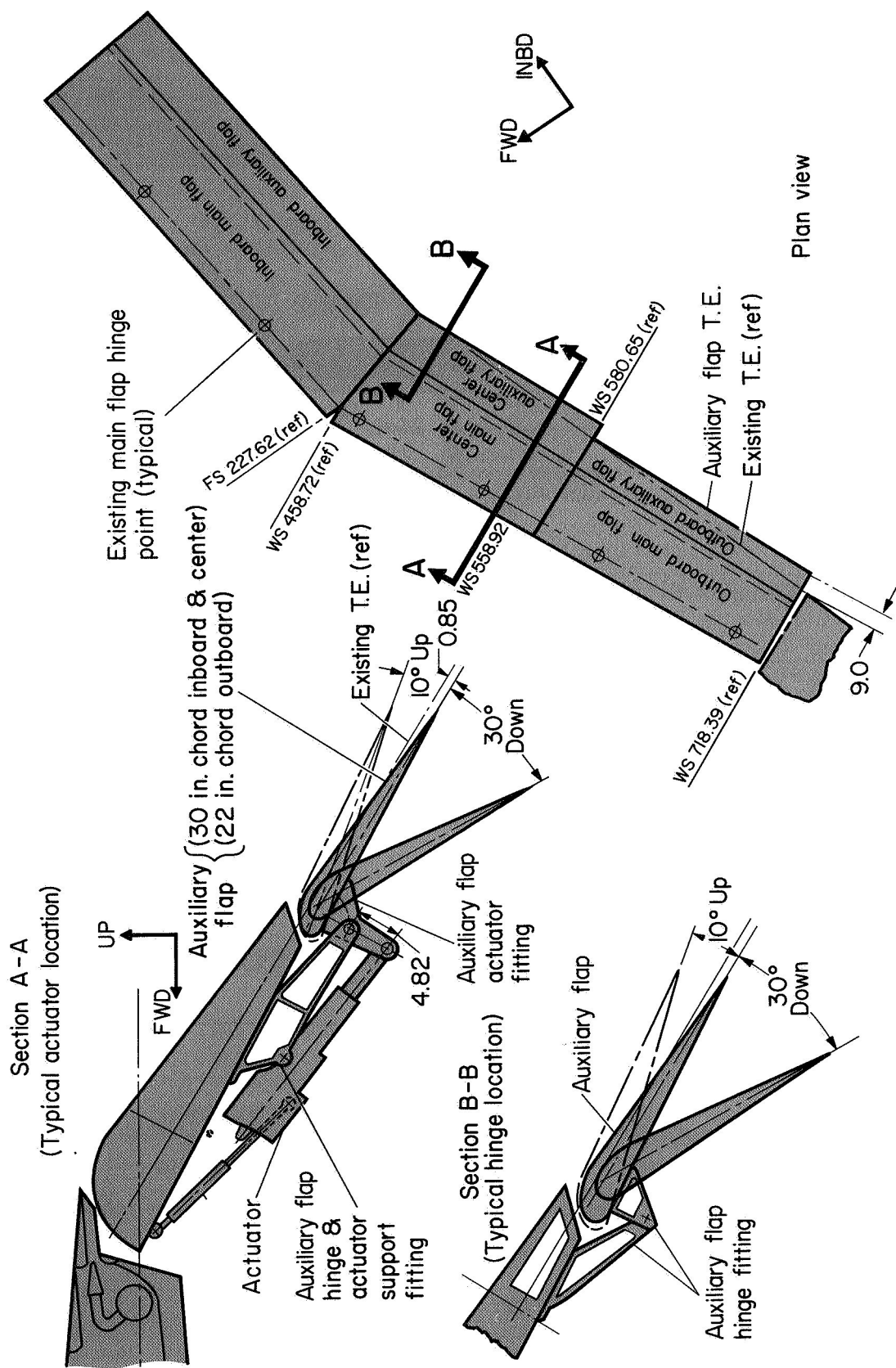
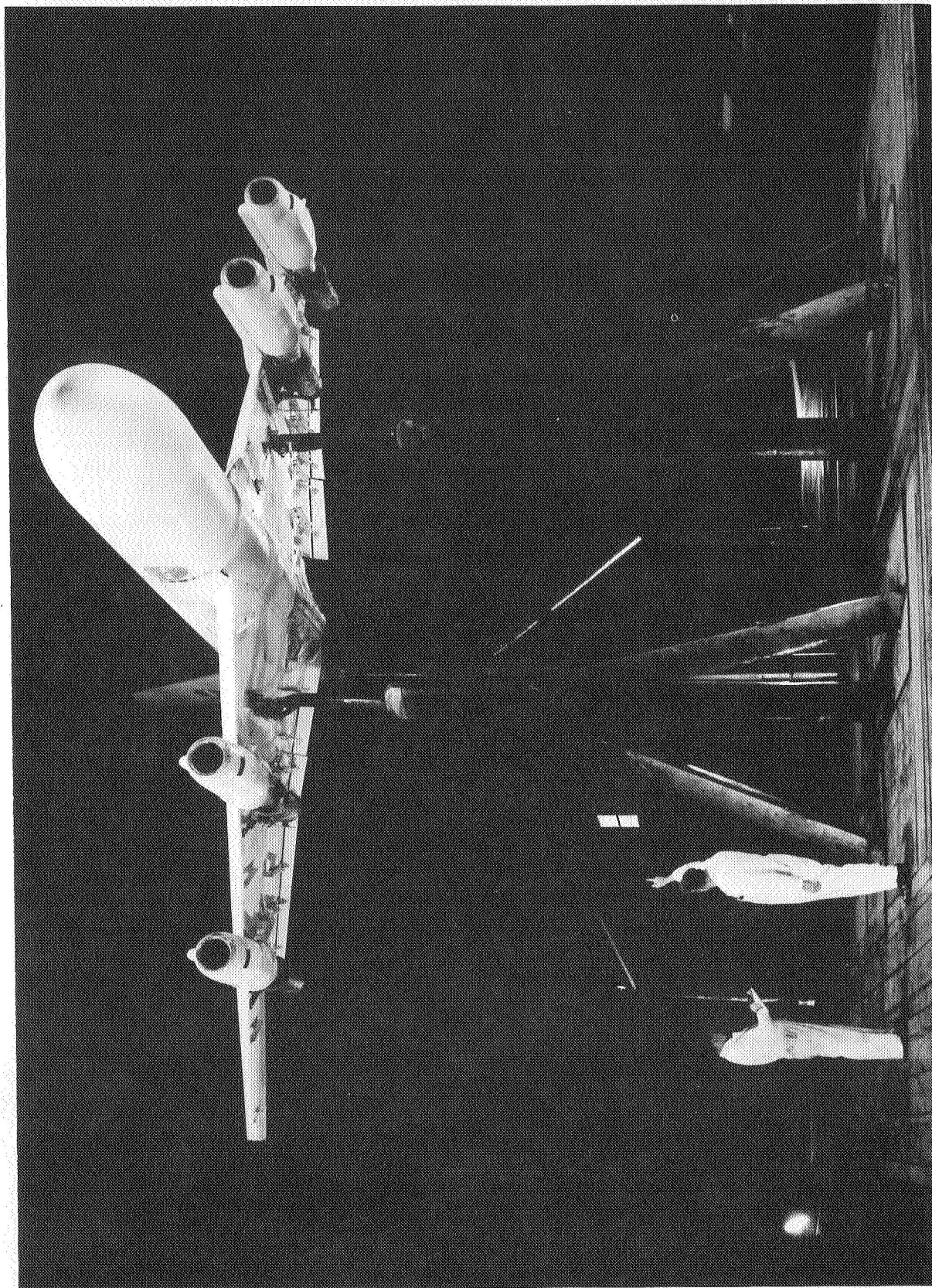
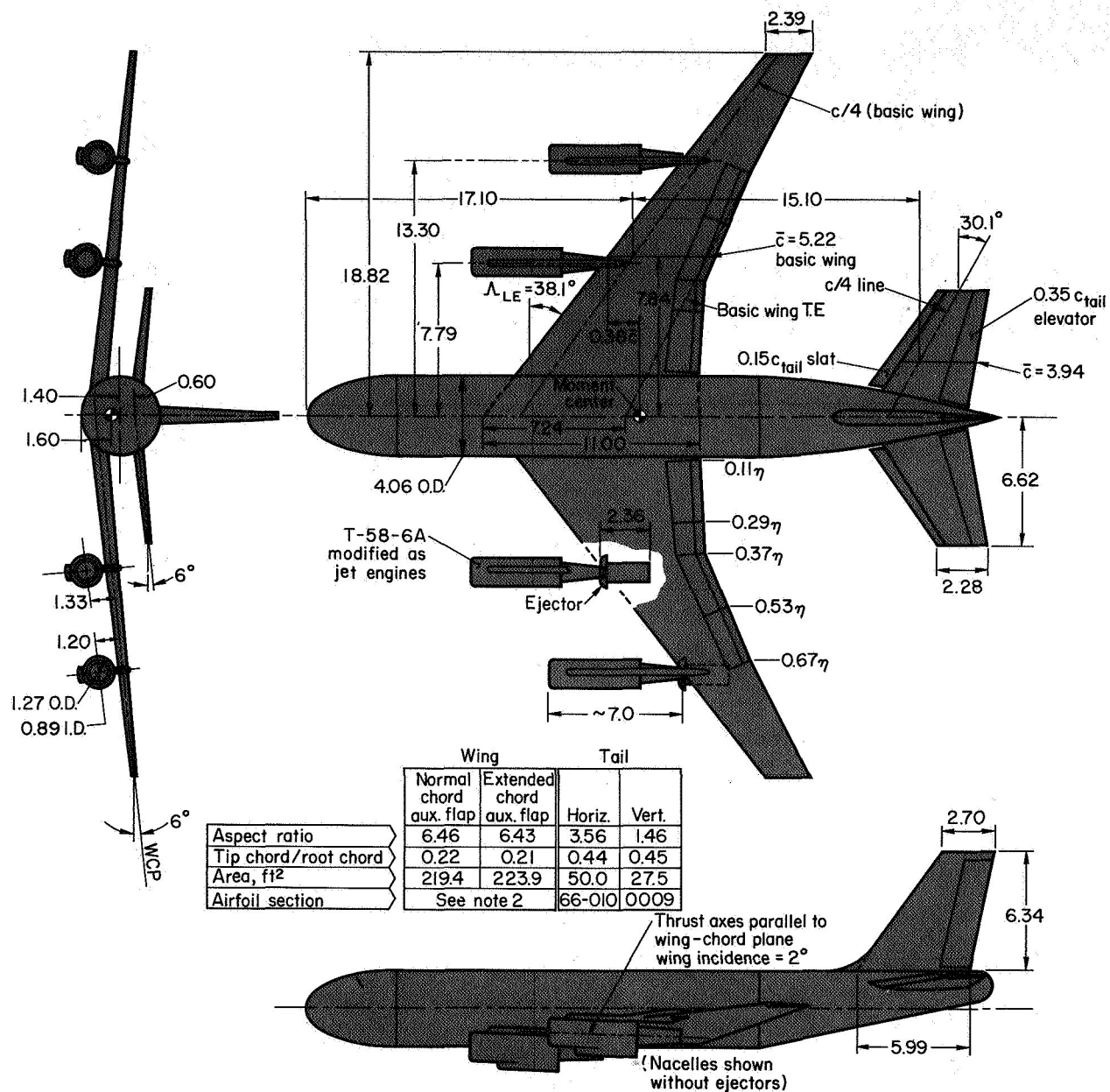


Figure 3.- Details of auxiliary flap system installed on airplane.



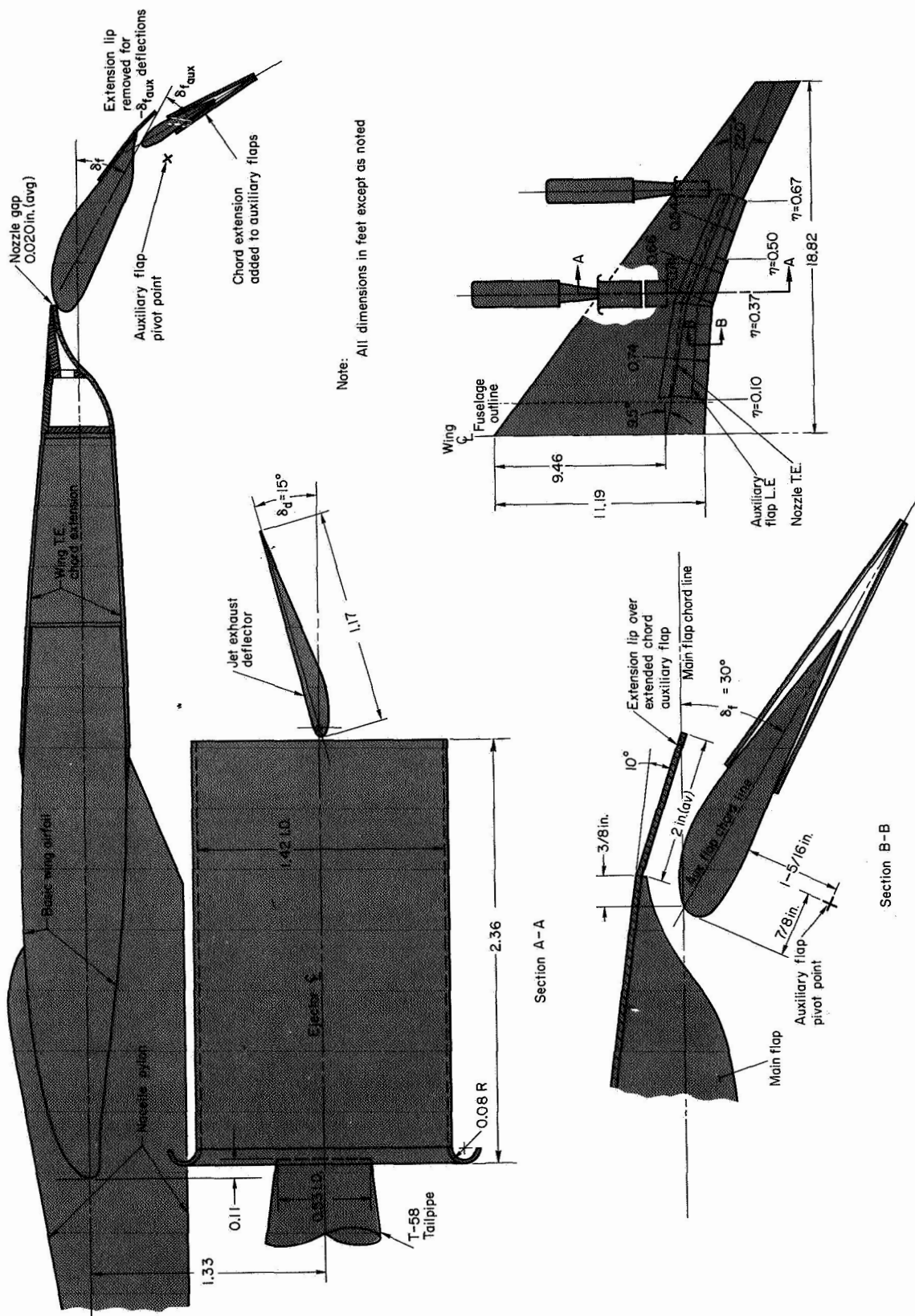
A-38281

Figure 4.- One-third-scale model mounted in the Ames 40- by 80-Foot Wind Tunnel.



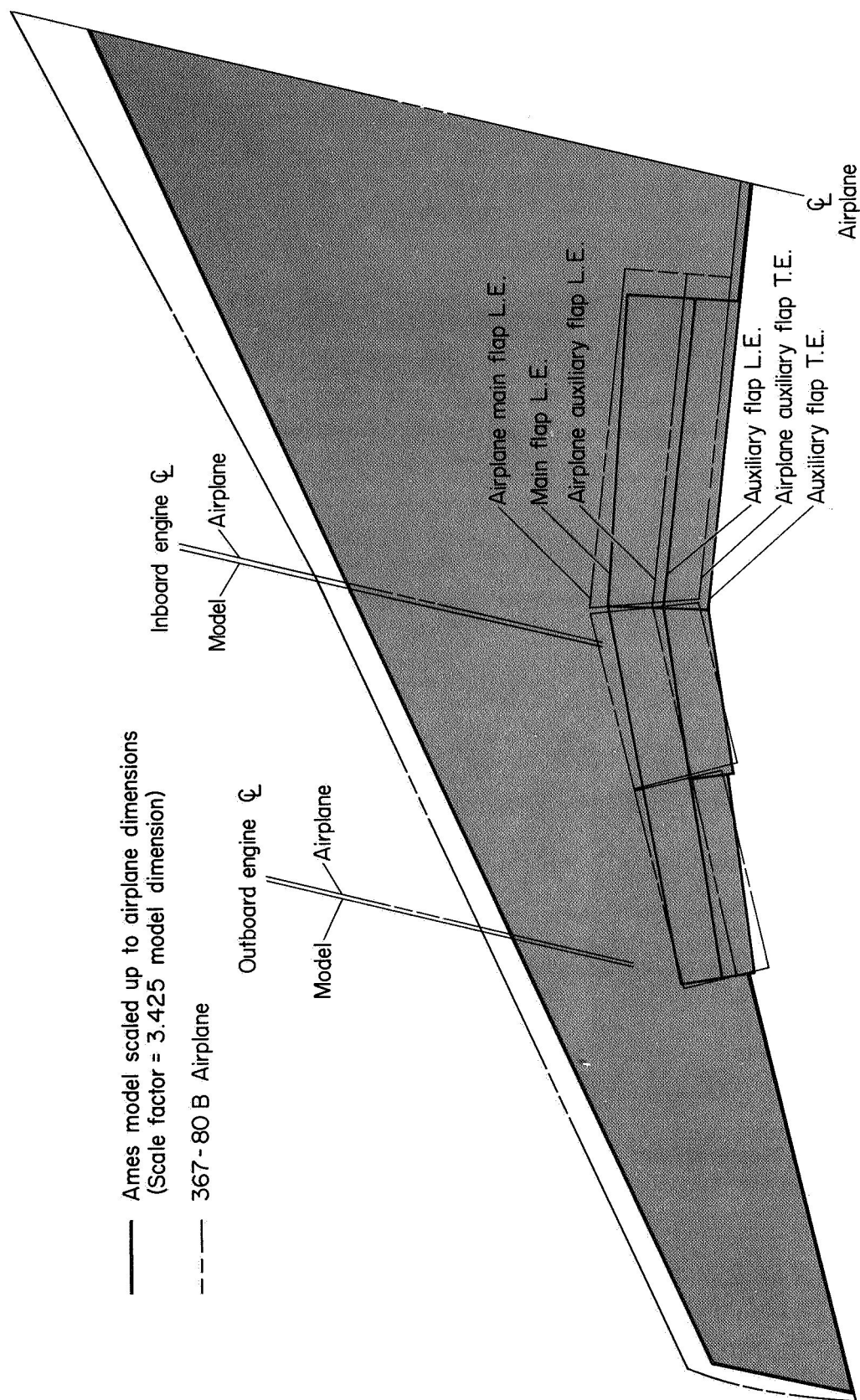
(a) General arrangement of model with normal chord auxiliary flap.

Figure 5.- Geometric details of the model.



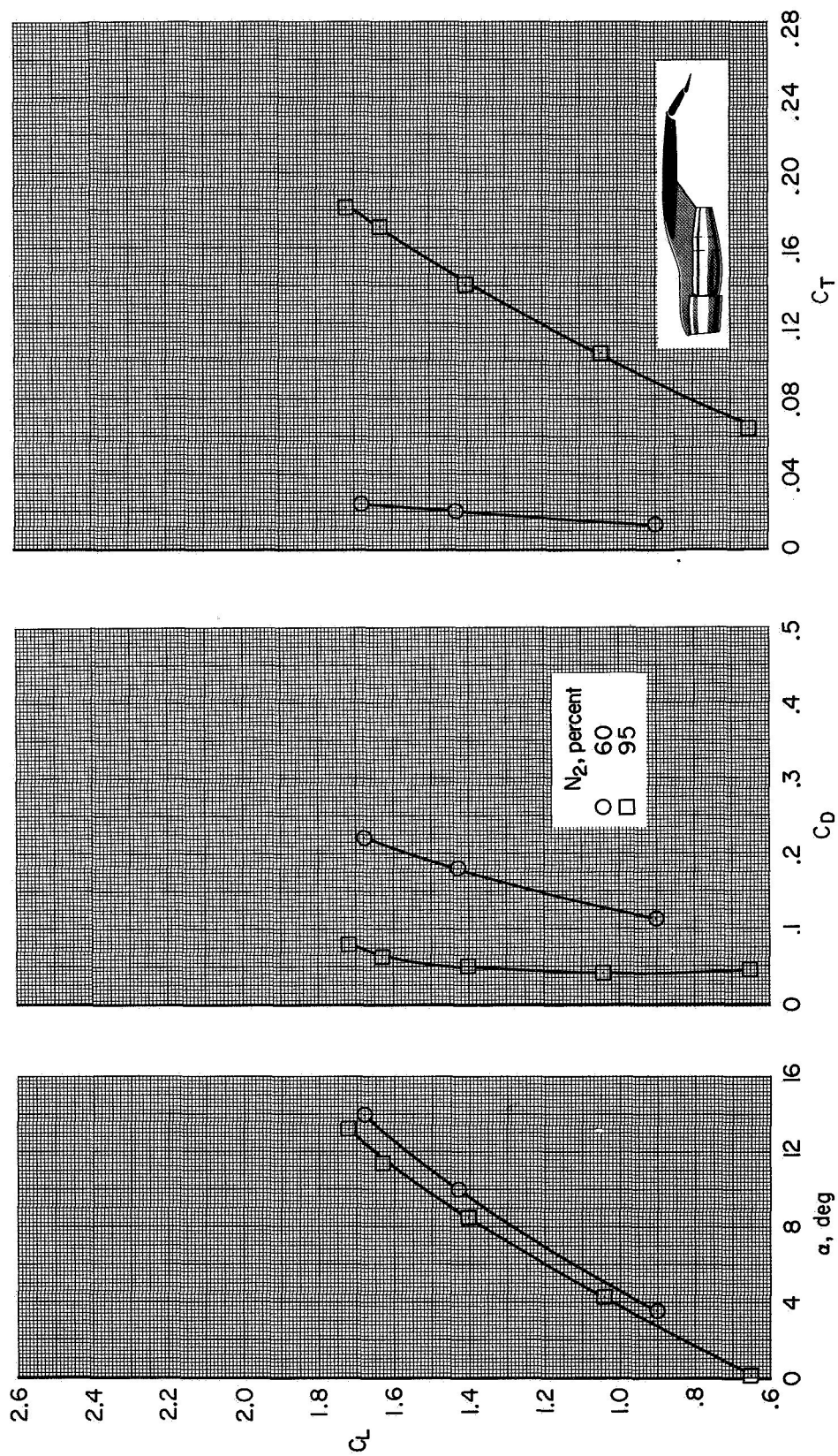
(b) Extended chord auxiliary flap arrangements.

Figure 5.- Continued.



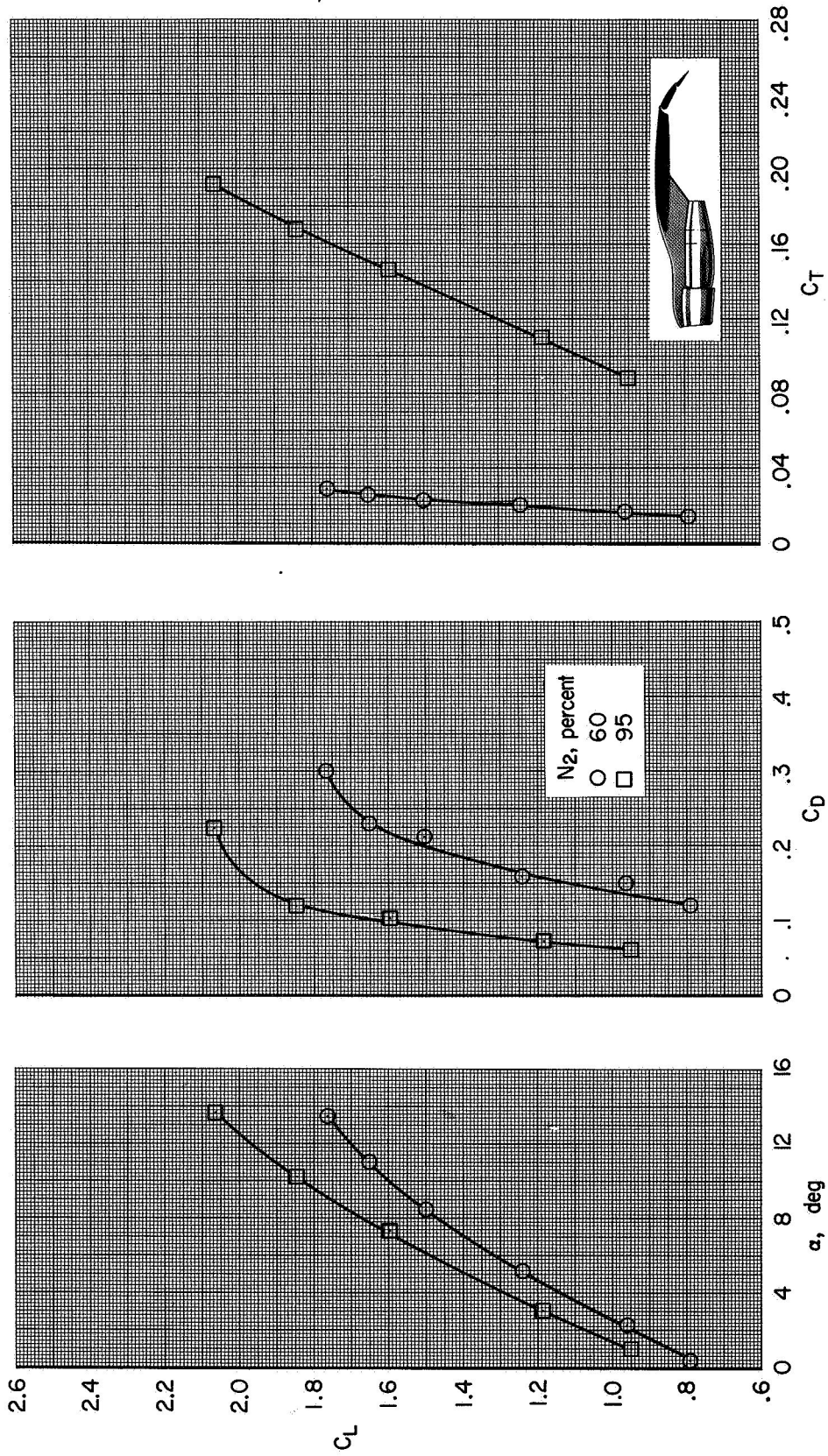
(c) Comparison of DLC flap planforms between Ames model and 367-80 B airplane.

Figure 5.- Concluded.

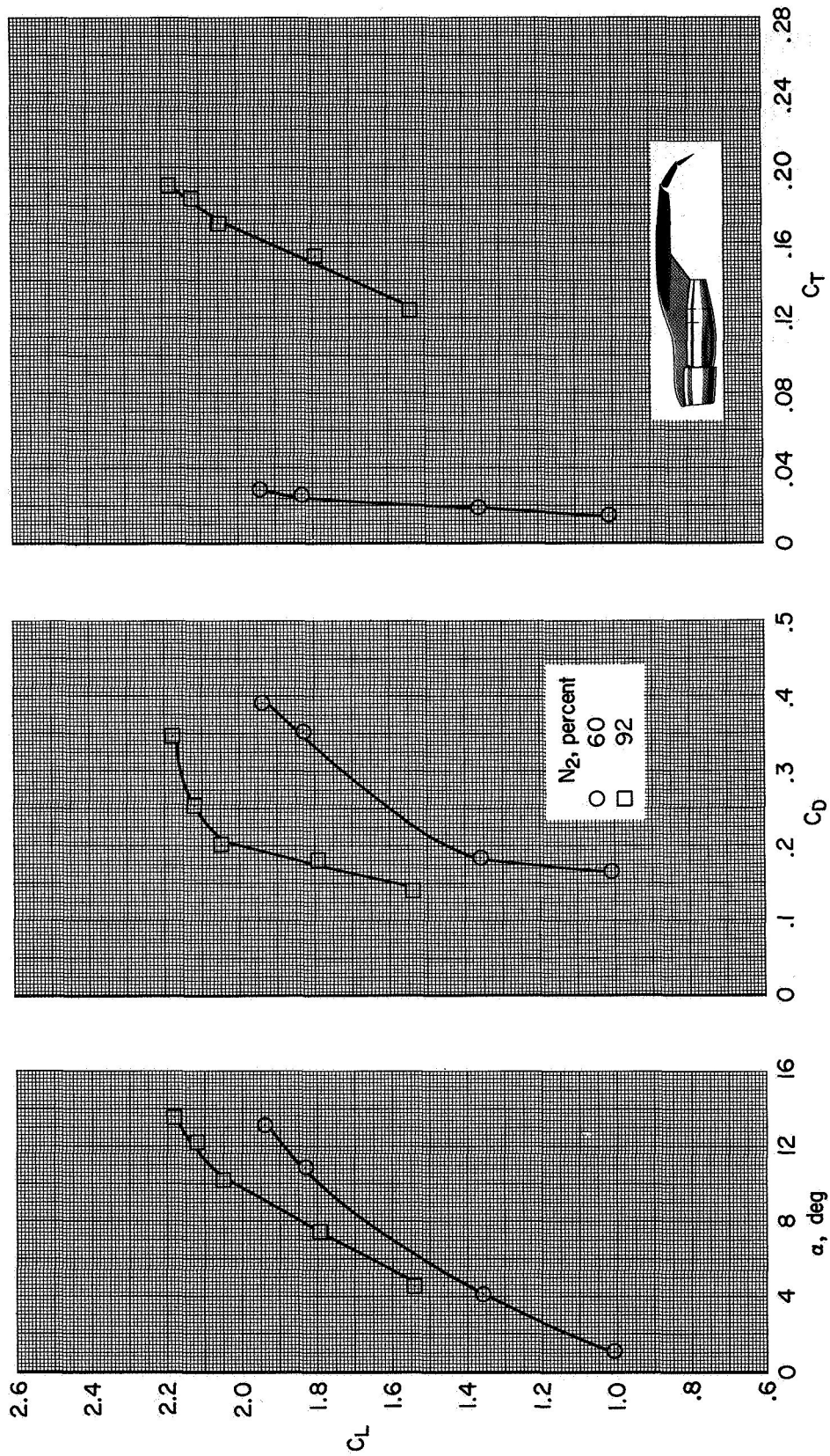


(a) $\delta_{\text{faux}} = -10^\circ$

Figure 6.- Basic aerodynamic data, measured in flight; main flaps at 30° .

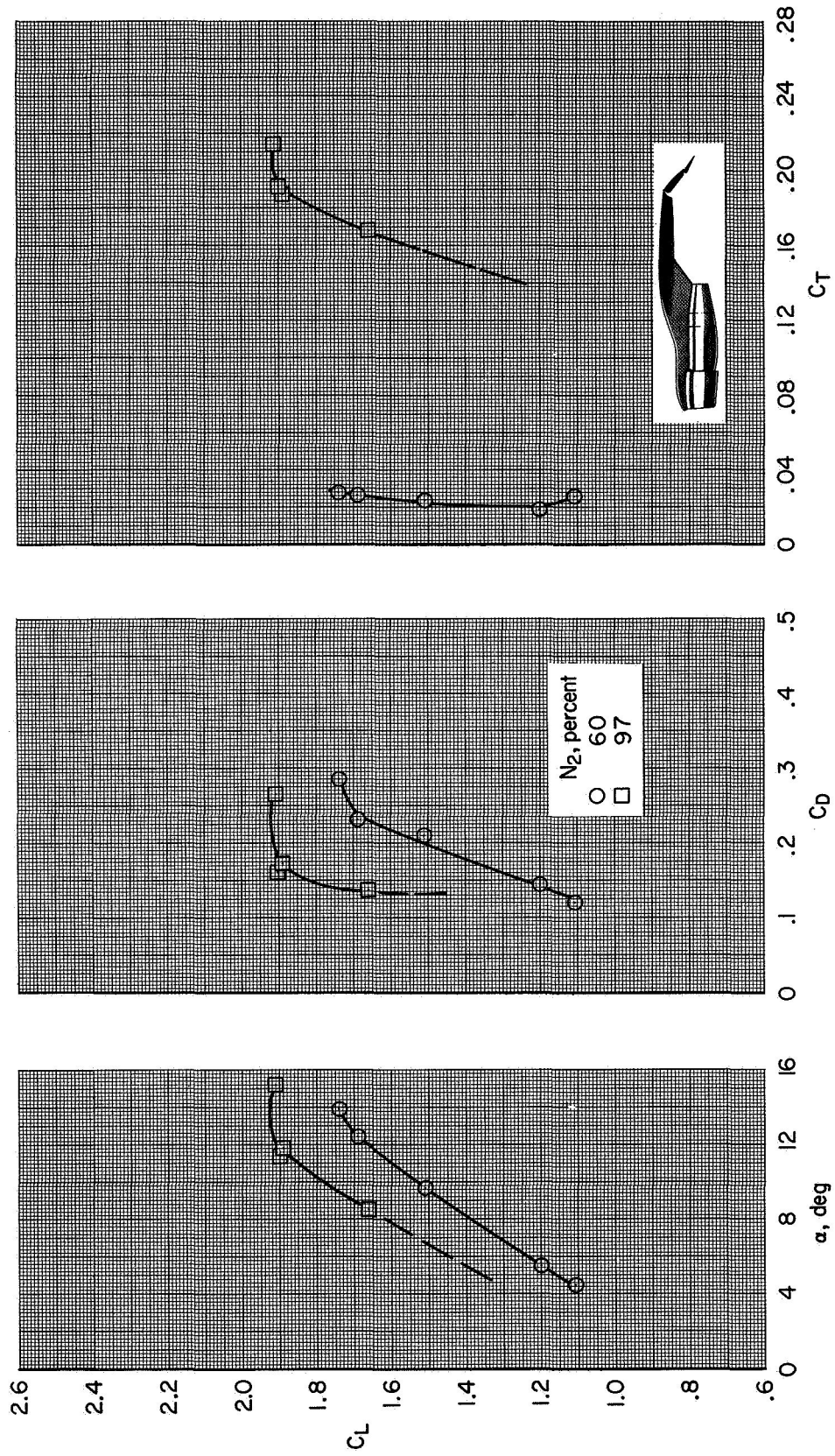


(b) $\delta_{\text{faux}} = 10^\circ$
Figure 6.- Continued.



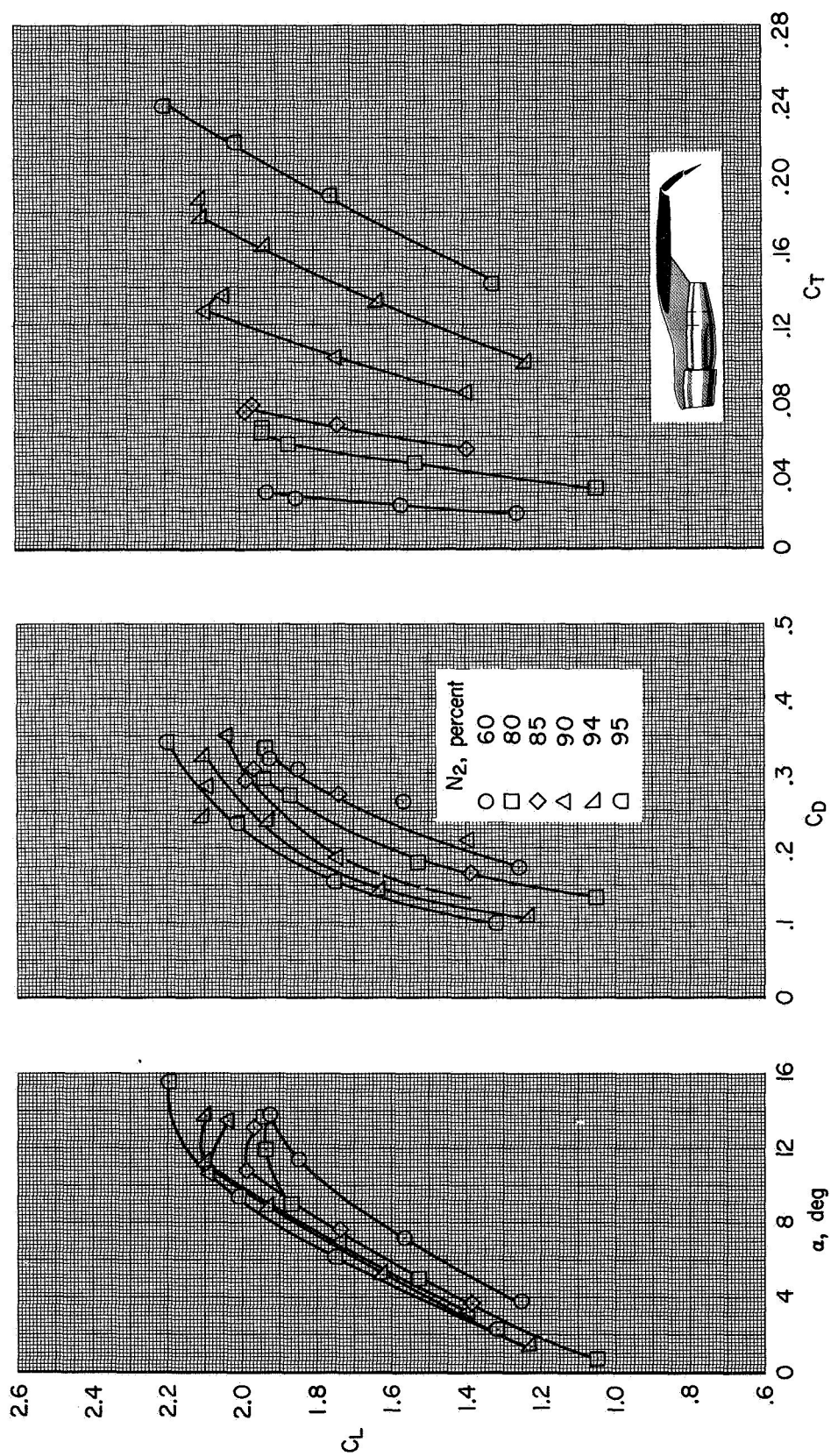
(c) $\delta f_{aux} = 30^\circ$

Figure 6.- Concluded.

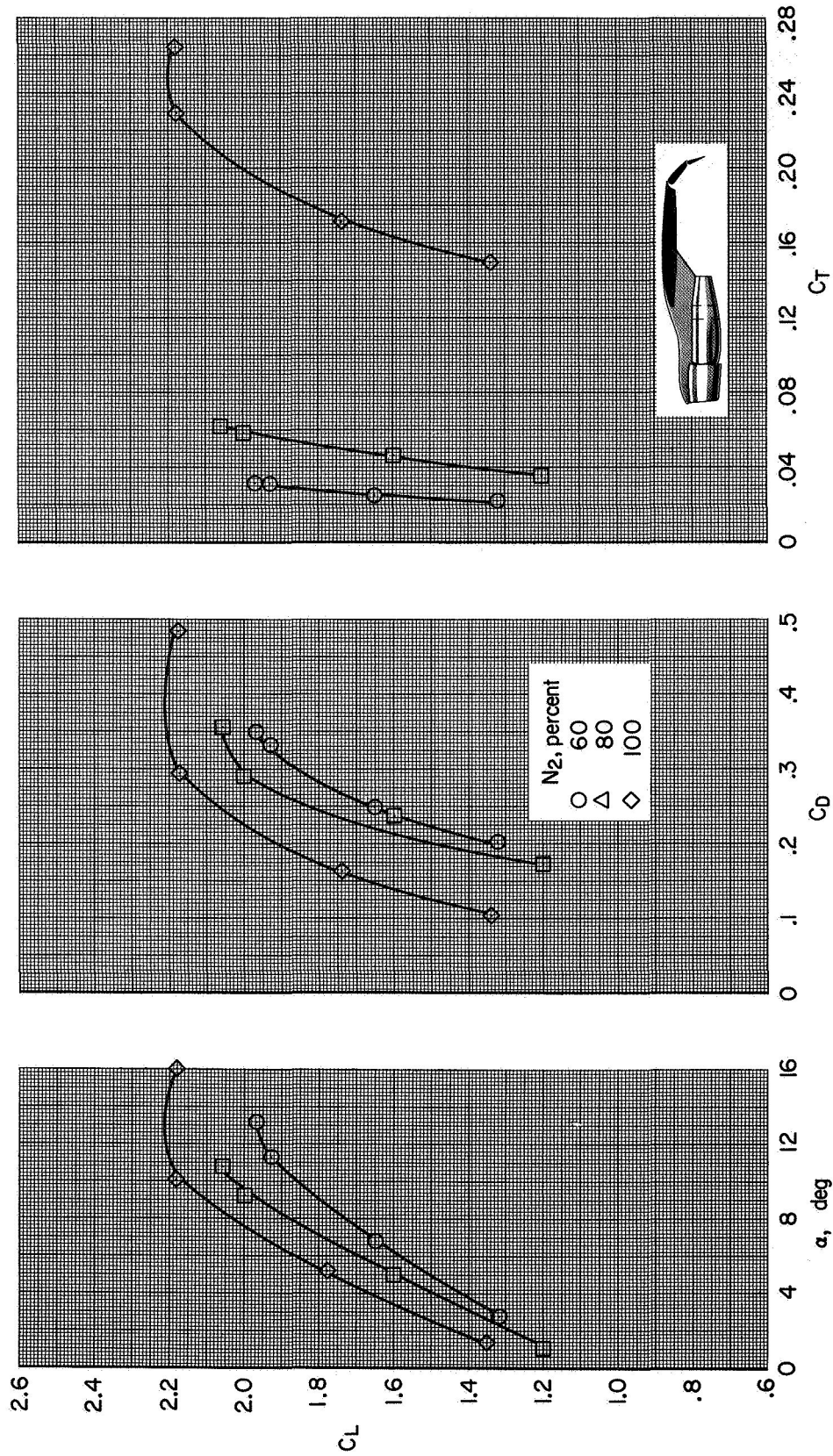


(a) $\delta_{f_{aux}} = -10^\circ$

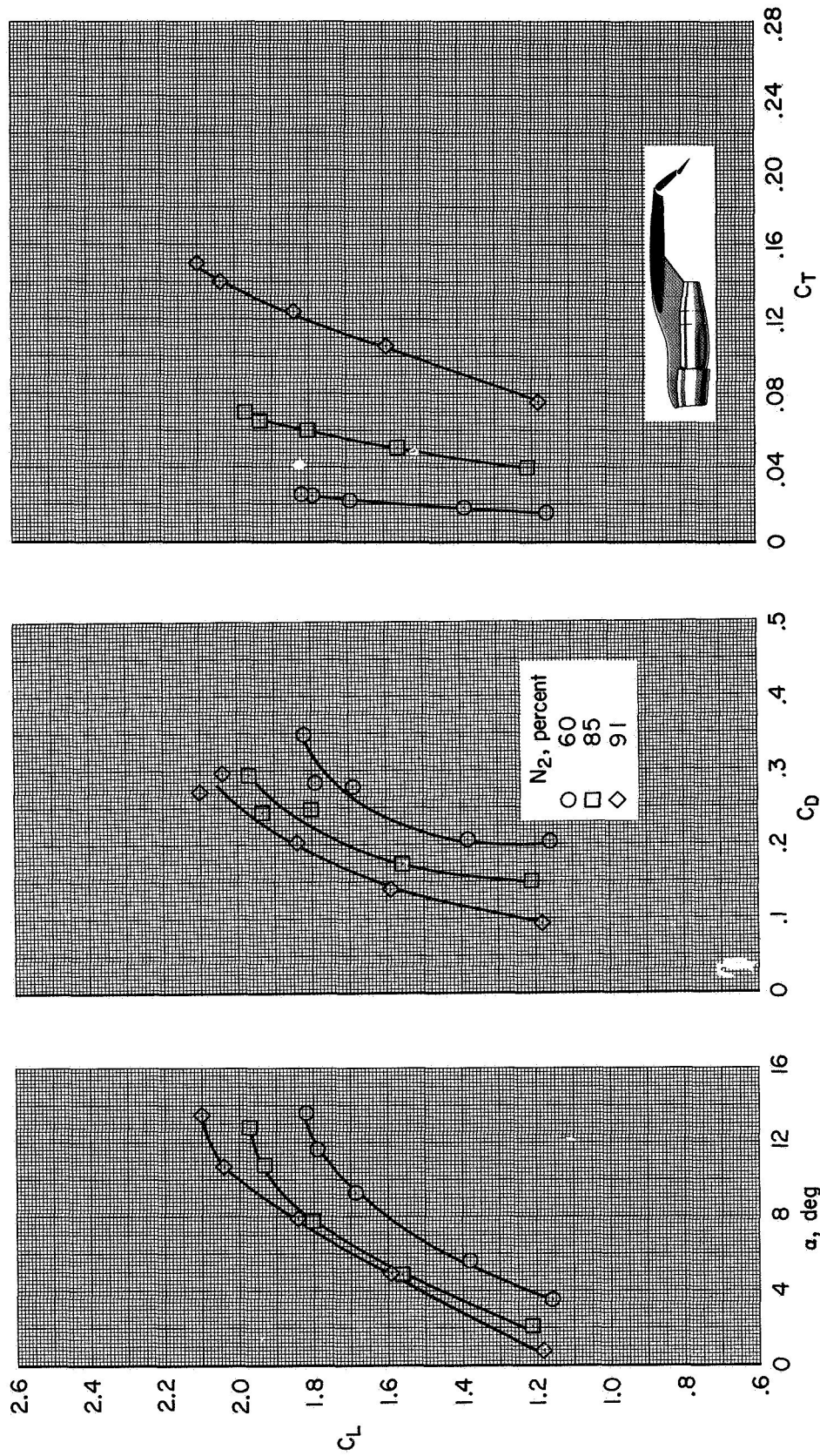
Figure 7.- Basic aerodynamic data measured in flight; main flaps at 40° .



(b) $\delta_{faux} = 10^\circ$
 Figure 7.- Continued.

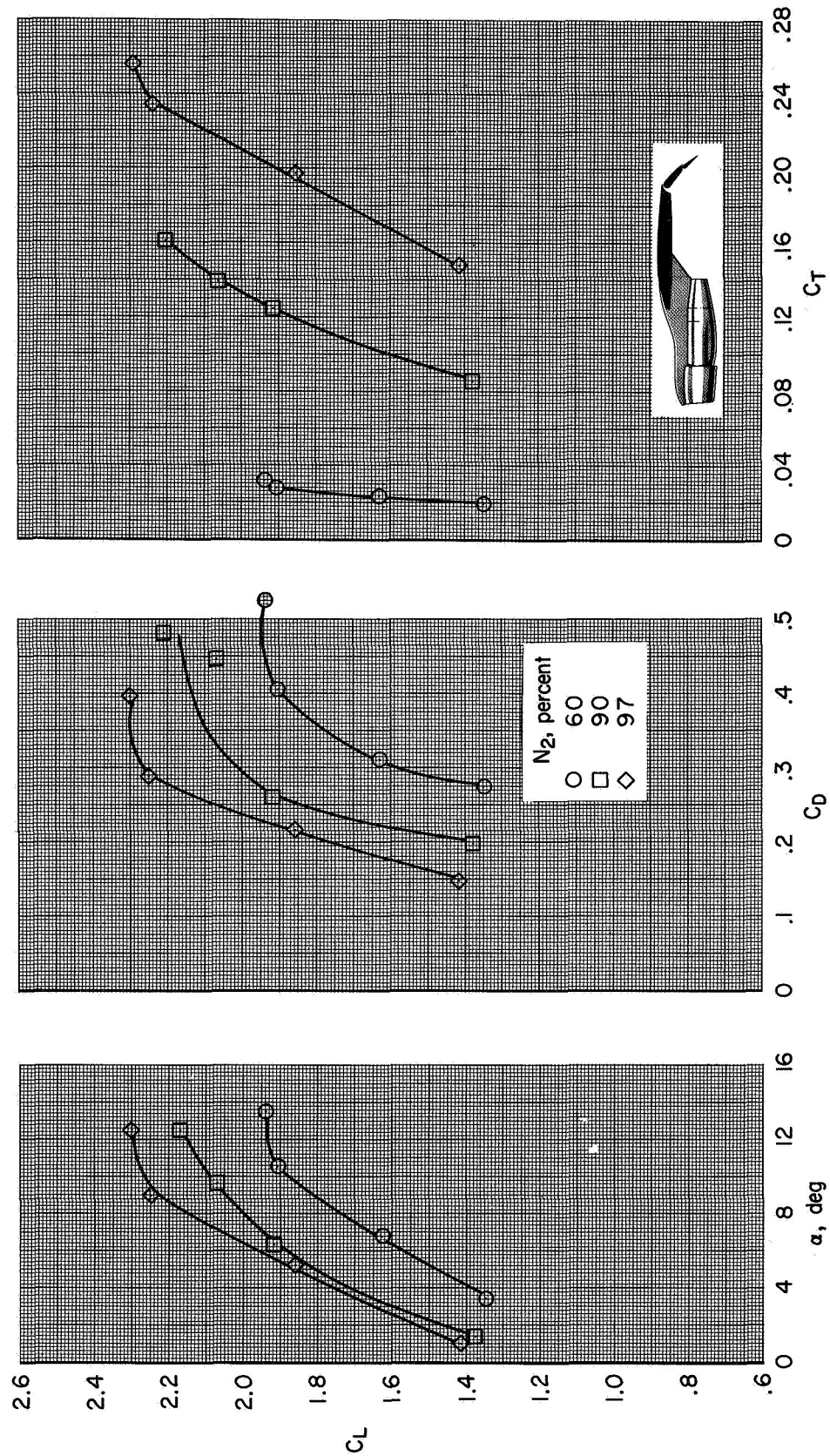


(c) $\delta_{f_{aux}} = 30^\circ$
Figure 7.- Concluded.

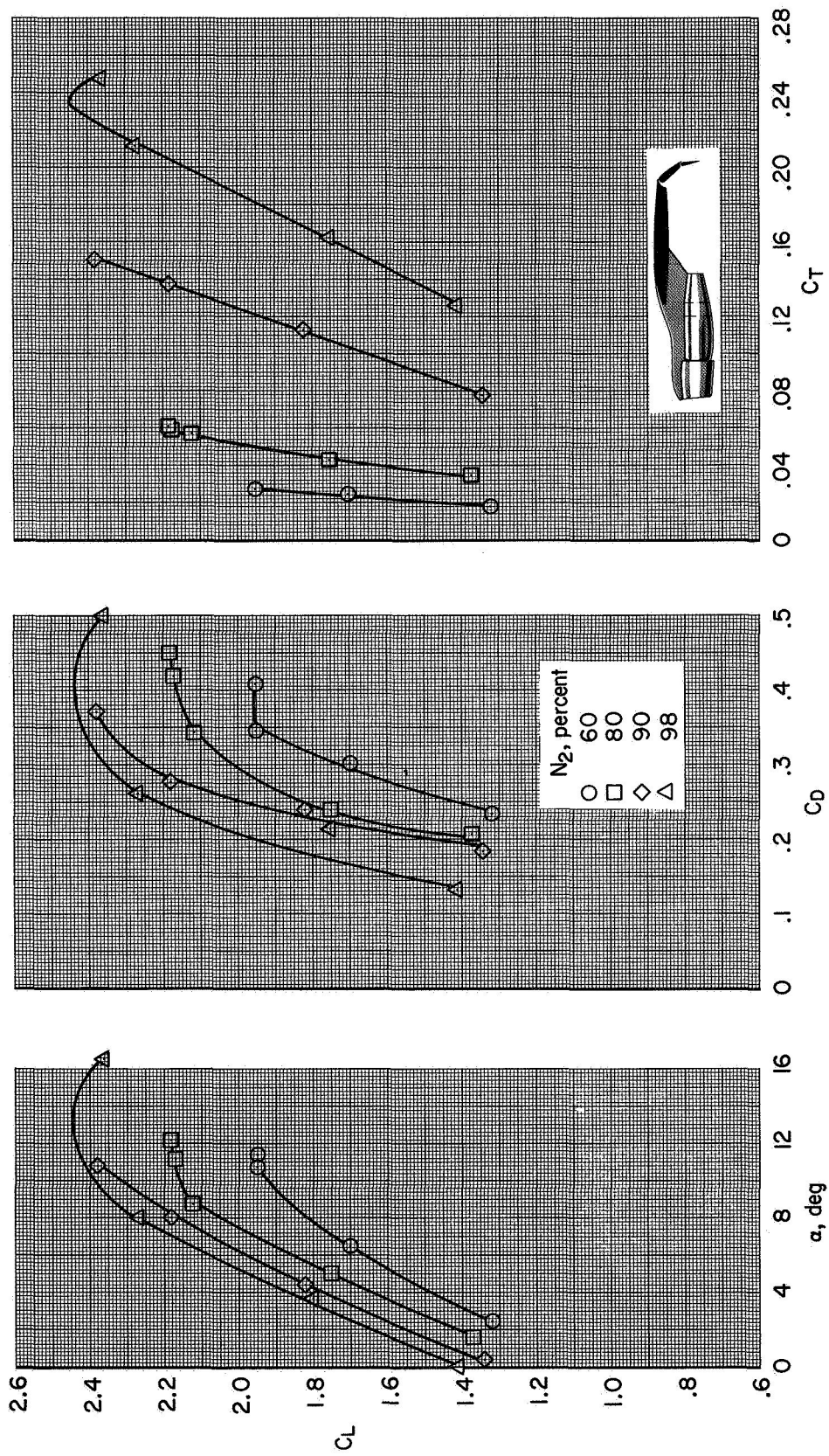


(a) $\delta_{f_{aux}} = -10^\circ$

Figure 8.- Basic aerodynamic data measured in flight; main flaps at 50° .



(b) $\delta f_{aux} = 10^\circ$
Figure 8.- Continued.



(c) $\delta_{f_{aux}} = 30^\circ$
Figure 8.- Concluded.

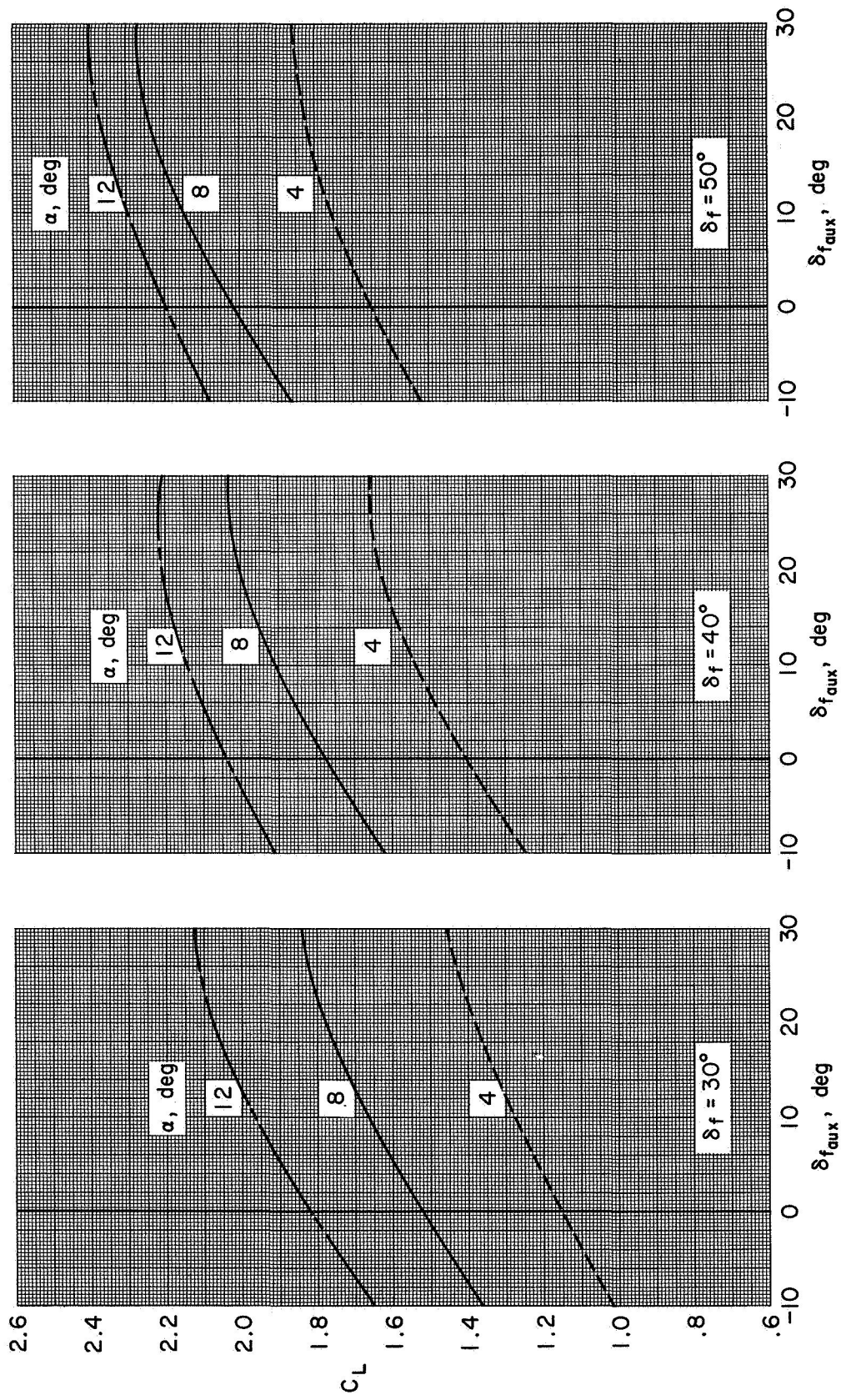


Figure 9.- Auxiliary flap effectiveness measured in flight.

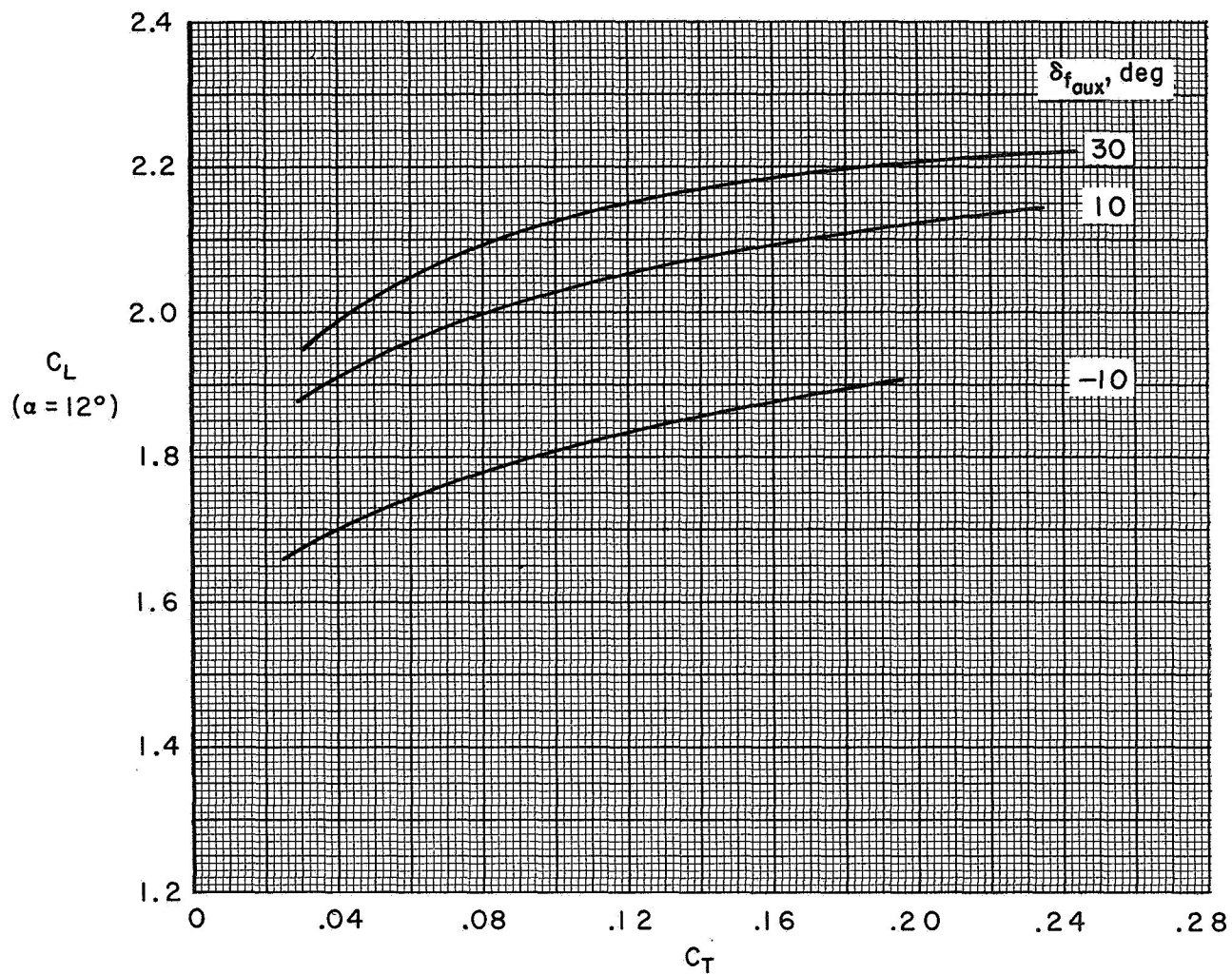


Figure 10.- Effect of thrust coefficient on lift characteristics of auxiliary flap system; main flap at 40° .

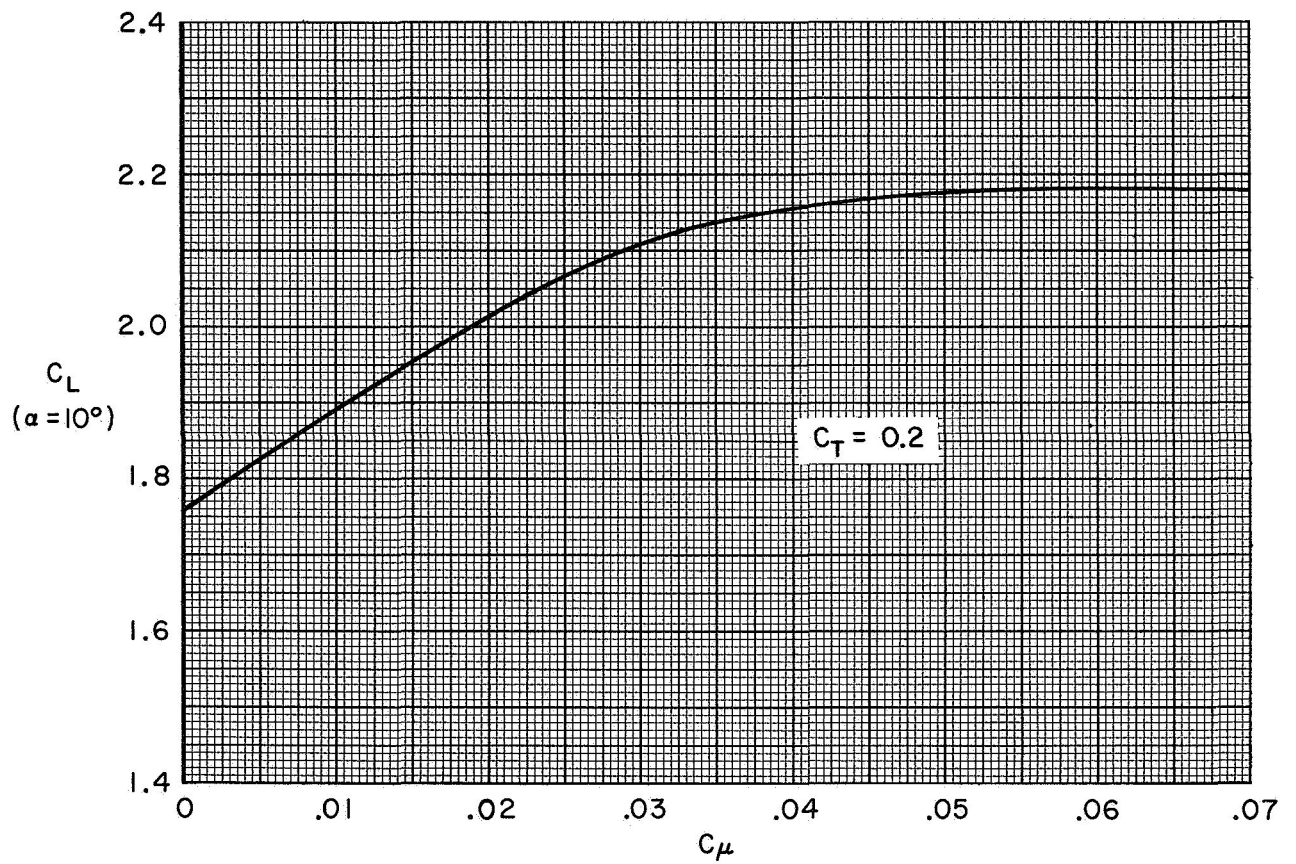


Figure 11.- Typical variation of lift coefficient with boundary-layer-control momentum coefficient; main flap at 50° , auxiliary flap at 10° .

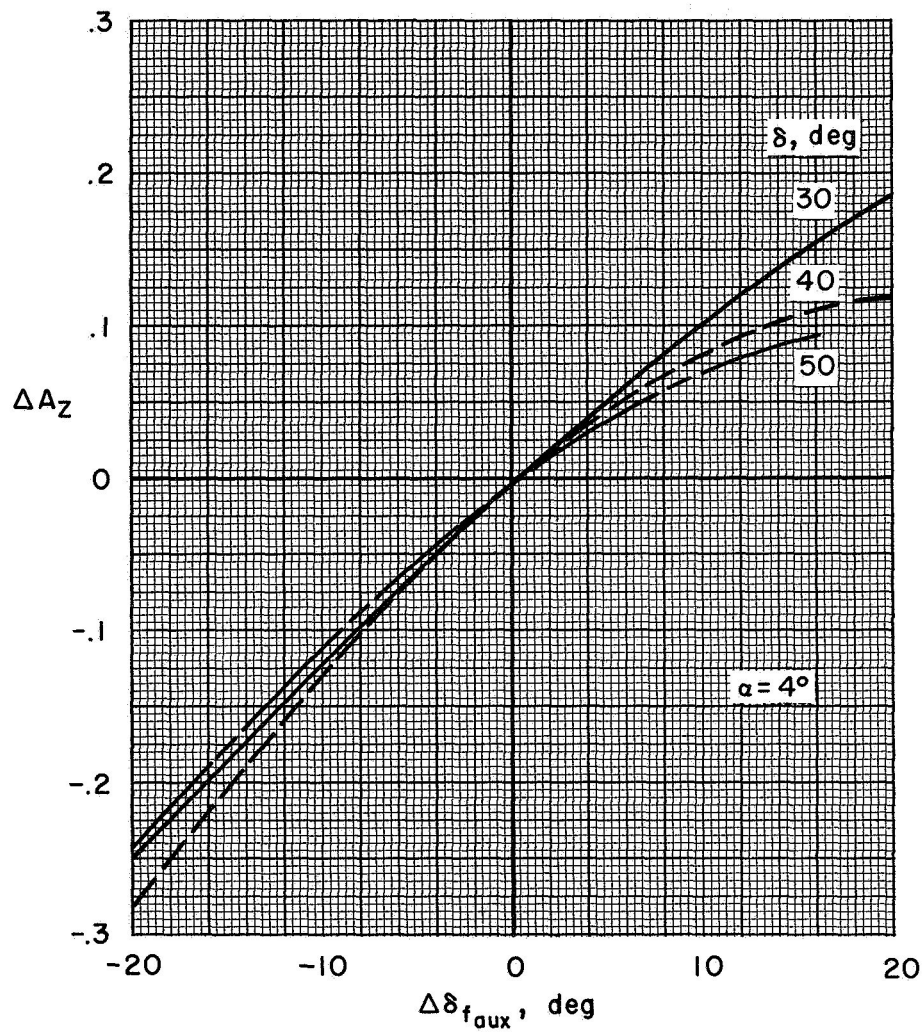


Figure 12.- Normal acceleration capability of the auxiliary flap system determined from steady flight data.

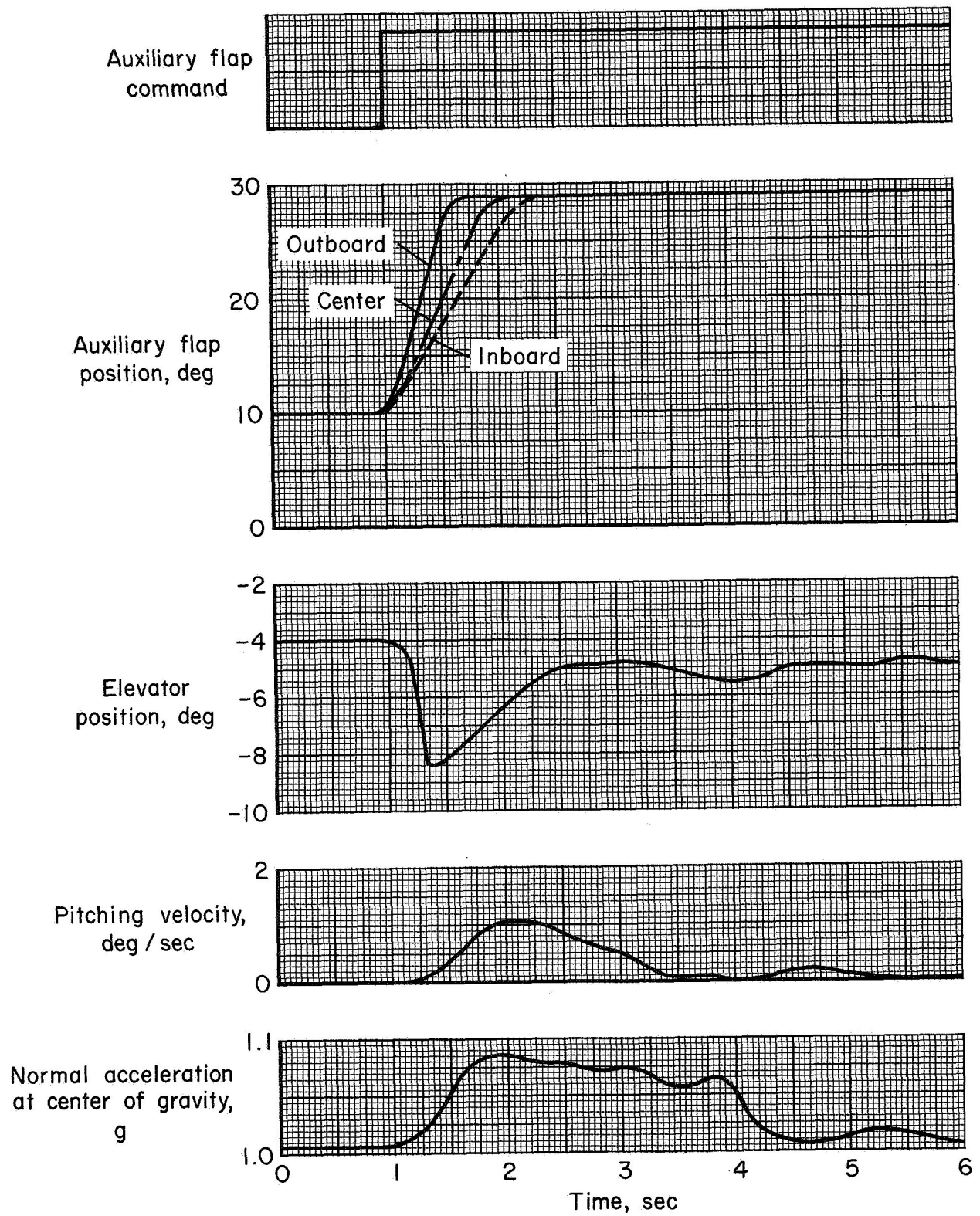
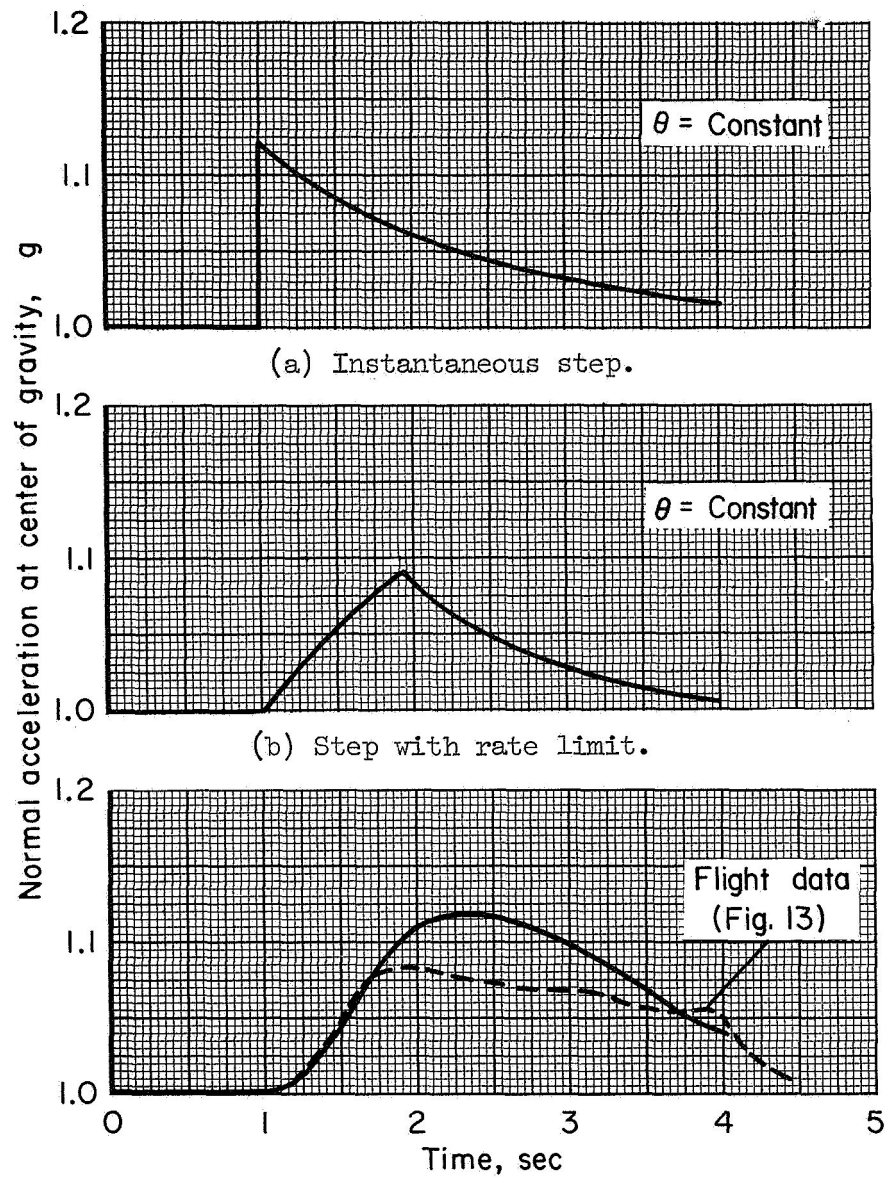
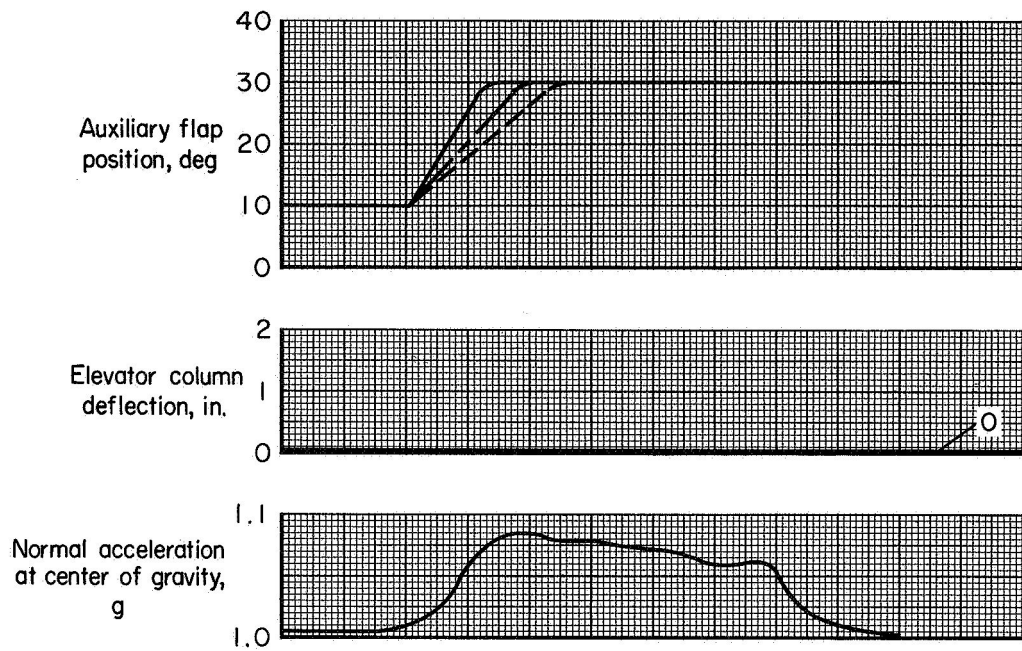


Figure 13.- Response of aircraft to an auxiliary flap step; main flap at 40° .

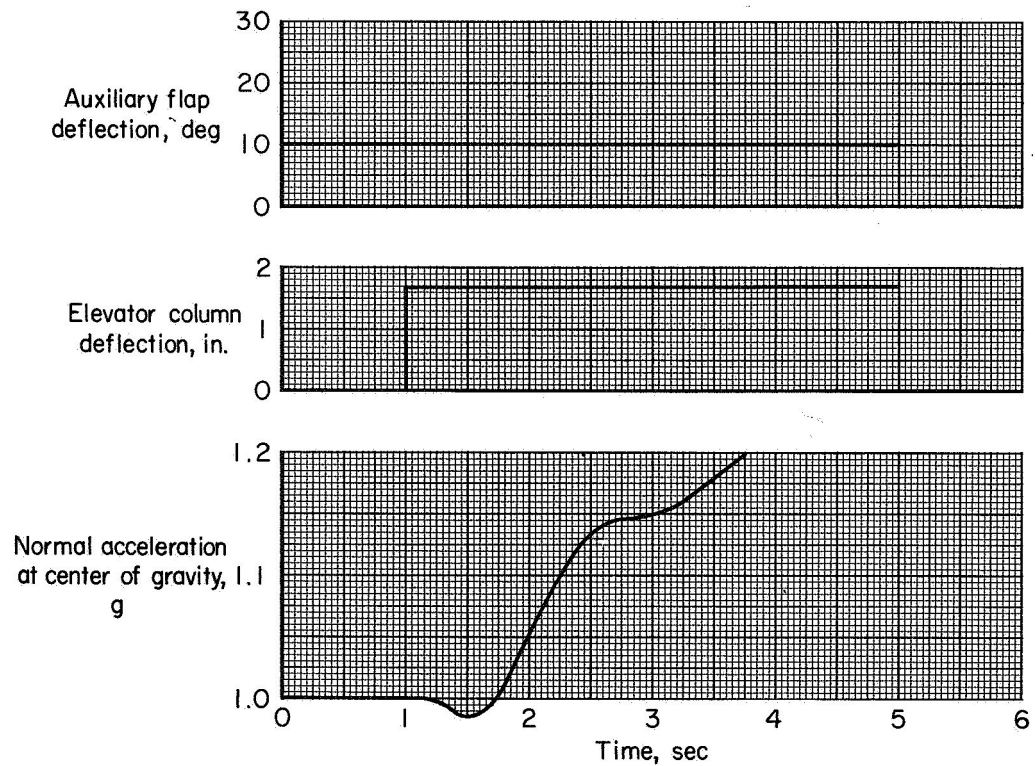


(c) Step with lag corrected for δ_F and θ effects on lift.

Figure 14.- Computed airplane responses to an abrupt auxiliary flap step.

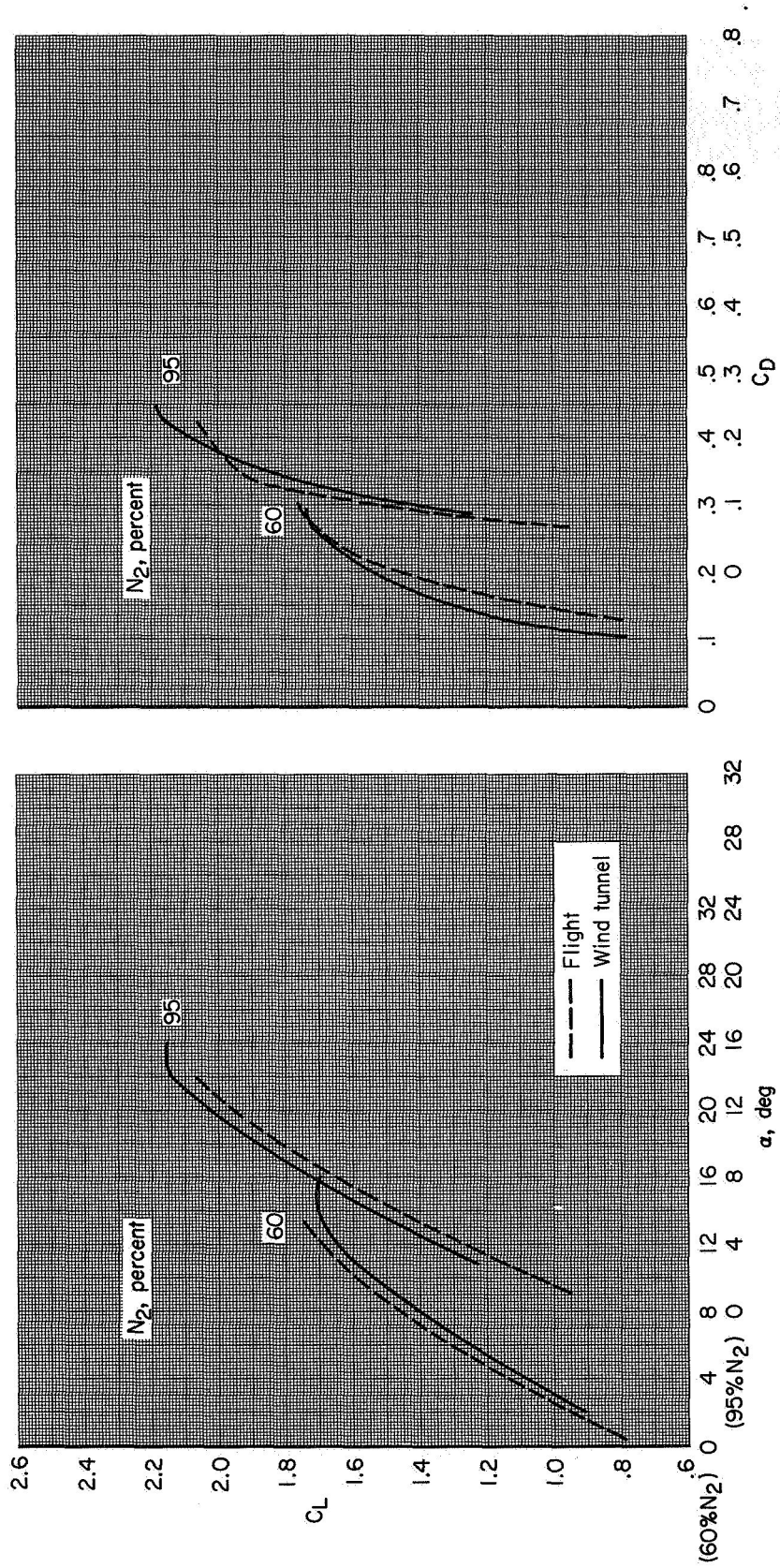


(a) Response to an auxiliary flap step.



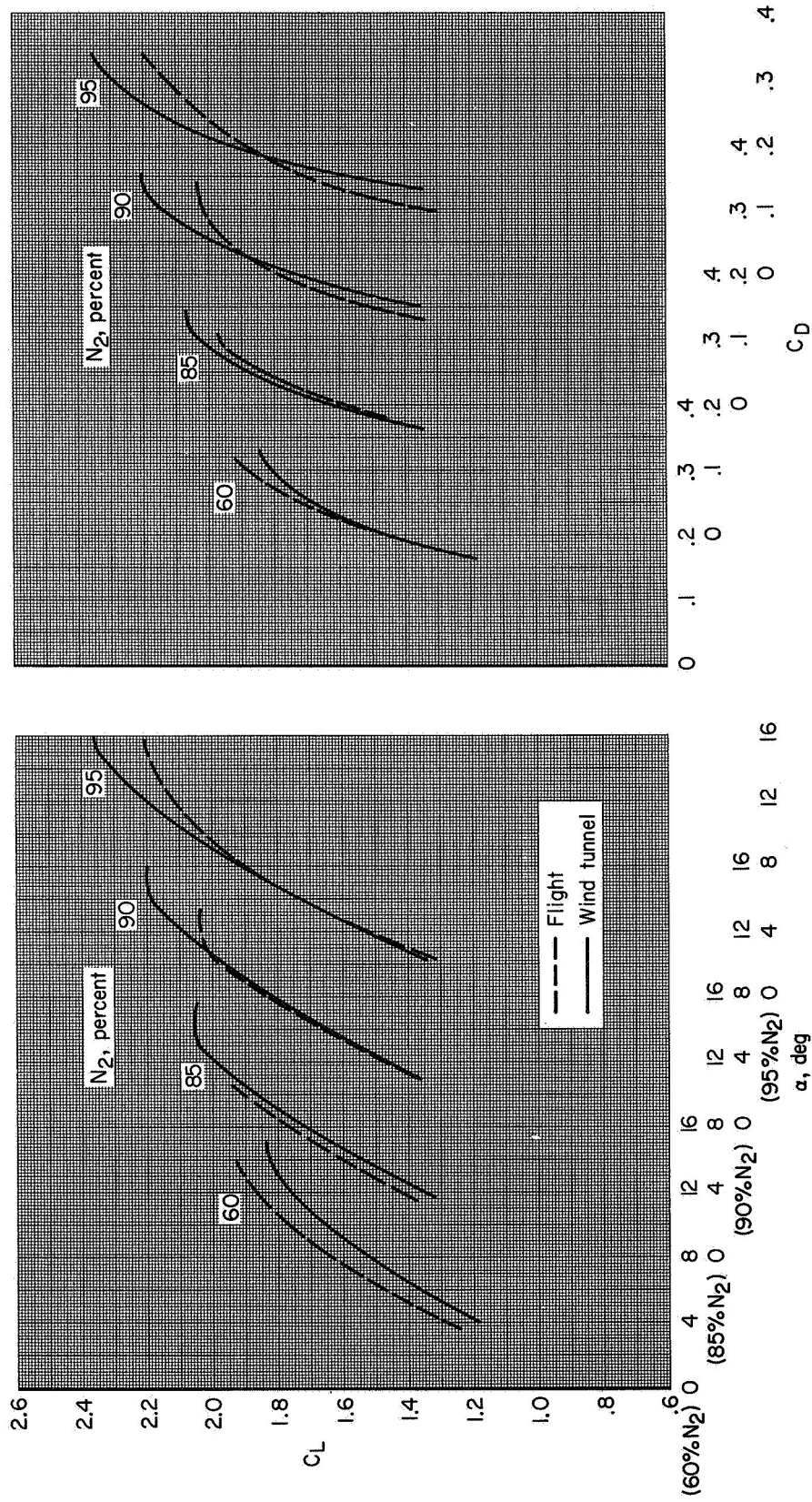
(b) Response to an elevator step.

Figure 15.- Comparison of the aircraft to an auxiliary flap step and to an elevator step.



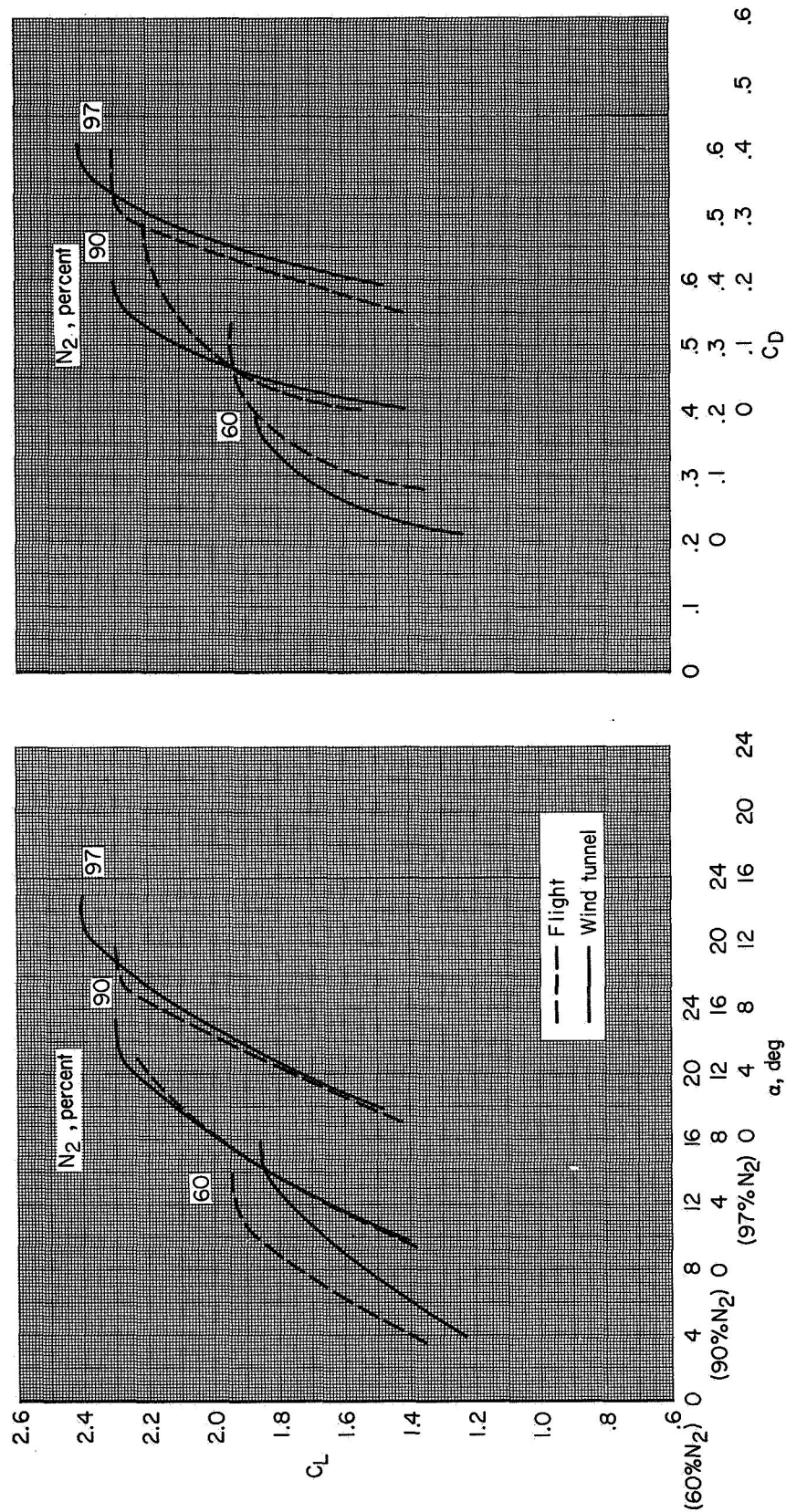
(a) $\delta_f = 30^\circ$, $\delta_{f_{aux}} = 10^\circ$

Figure 16.- Comparison of the lift and drag characteristics measured in the wind tunnel and in flight.



(b) $\delta_F = 40^\circ$, $\delta_{Faux} = 10^\circ$

Figure 16.- Continued.



(c) $\delta_f = 50^\circ$, $\delta_{faux} = 10^\circ$

Figure 16.- Concluded.

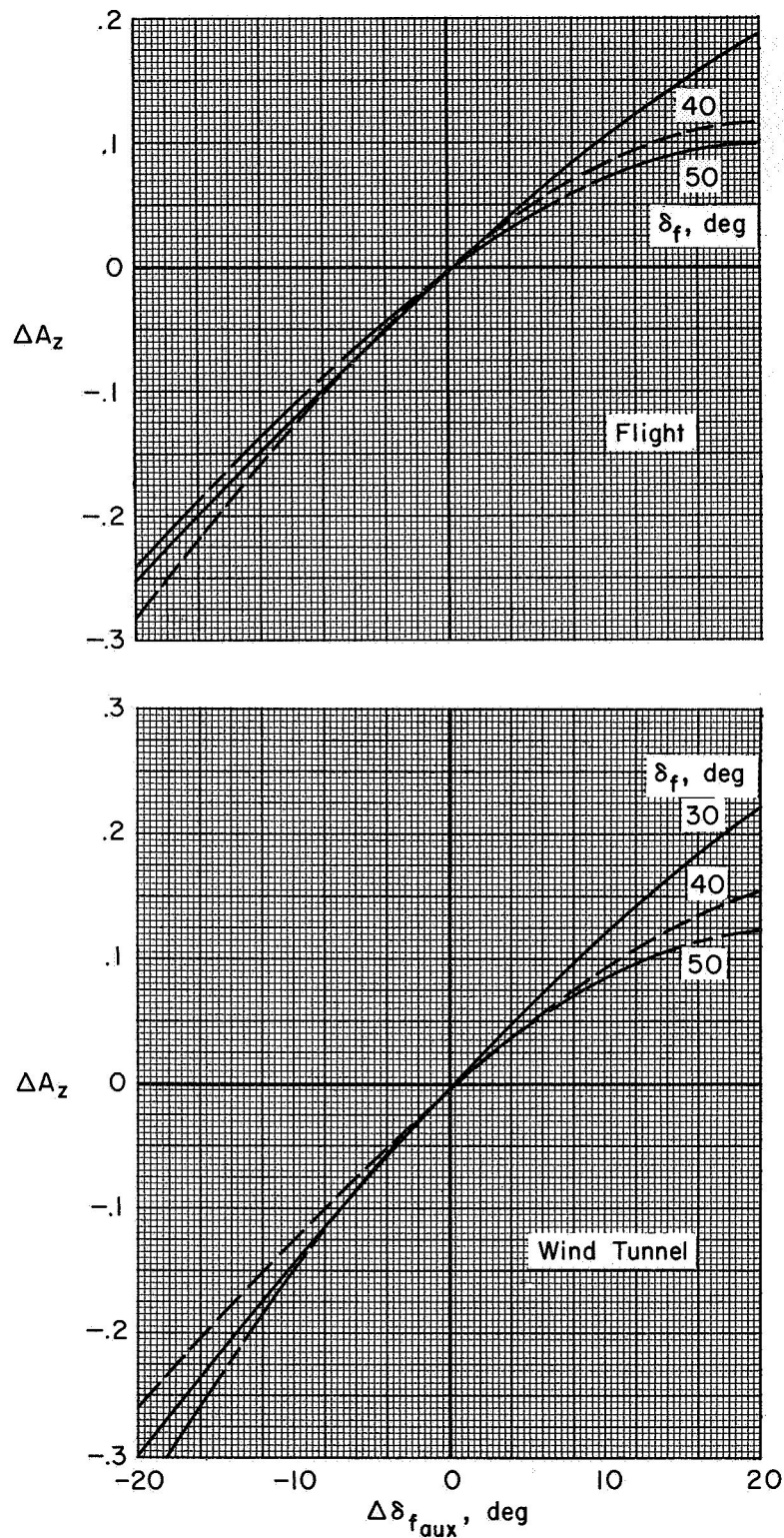


Figure 17.- Comparison of the normal acceleration capabilities determined in the wind tunnel and in flight.

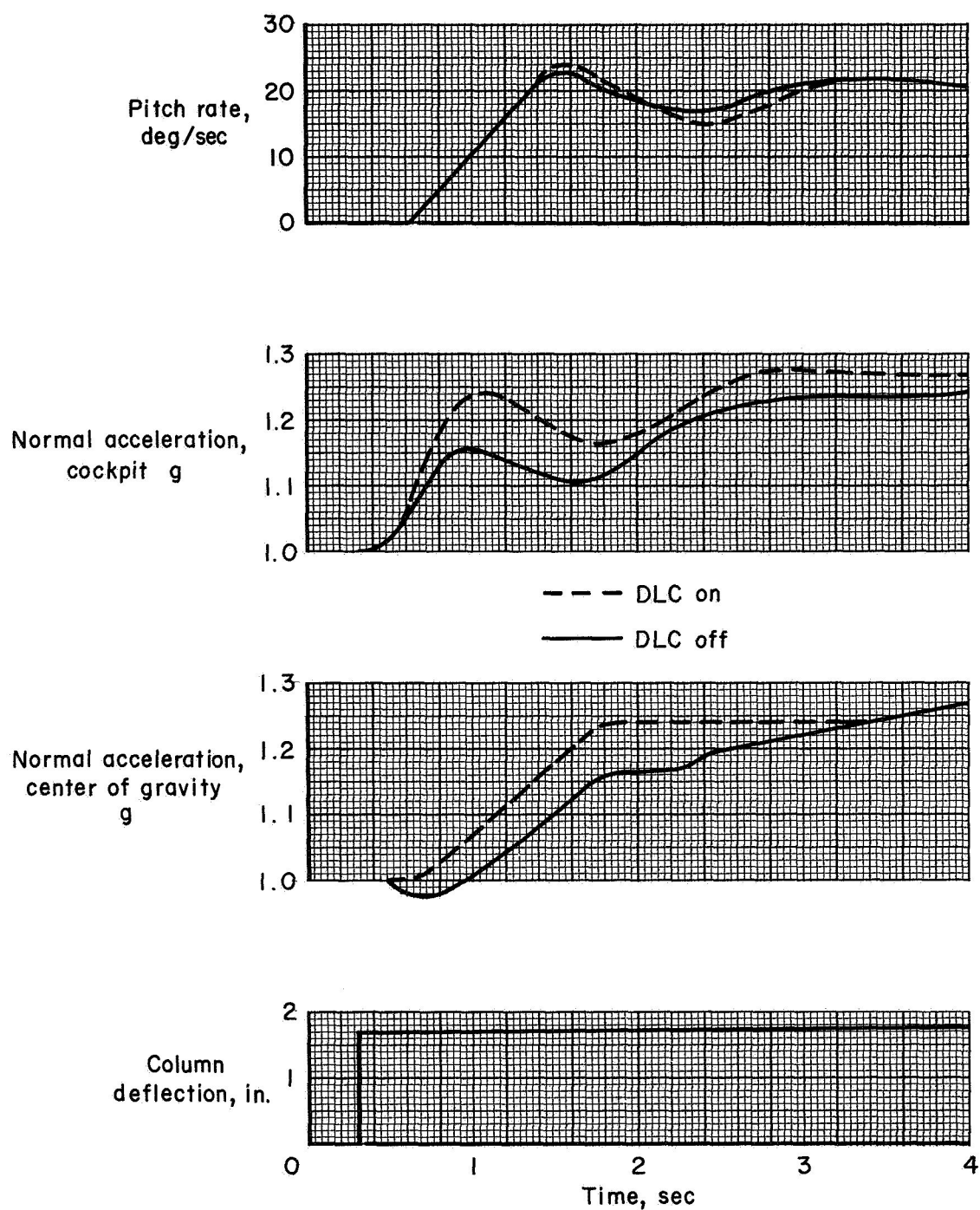


Figure 18.- Comparison of airplane response to an elevator step with DLC on and off; $\delta_F = 40^\circ$; SAS on, $V \approx 120$ knots, $W = 175,000$ lb.

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